ADAPTING ADA ARCHITECTURAL DESIGN KNOWLEDGE TO PRODUCT DESIGN: GROUNDWORK FOR A FUNCTION BASED APPROACH

A Thesis

by

SHRADDHA CHANDRAKANT SANGELKAR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Daniel A. McAdams
Committee Members,	Julie Linsey
	Laura Stough
Head of Department,	Dennis O' Neal

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ABSTRACT

Adapting ADA Architectural Design Knowledge to Product Design: Groundwork for a Function Based Approach. (August 2010)

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Chair of Advisory Committee: Dr. Daniel A. McAdams

Disability is seen as a result of an interaction between a person and that person's contextual factors. Viewing disability in the context of the built environment, a better design of this environment helps to reduce the disability faced by an individual. In spite of significant research in Universal Design (UD), the existing methods provide insufficient guidance for designers: designers demand more specific examples of, and methods for, good universal design.

Within the overarching goal of improving universal product design, the specific goal of this research is to determine if the ADA guidelines for architectural design can be adapted to product design. A methodology that foresees the accessibility issues while designing a product would be constructive. The new technique should be built on the pre-existing principles and guidelines.

A user activity and product function framework is proposed for this translation using actionfunction diagrams. Specific goals include determining if the function-based approach is able to anticipate a functional change that improves product accessibility.

Further, generate user activity and product function association rules that can be applied to the universal design of products.

Proposed research activities are to identify thirty existing universal products and compare with its typical version to identify the function that introduces an accessibility feature. Next, categorize the observed changes in a product function systematically and extract trends from accessible architectural systems to generate rules for universal design of consumer products. For validation, the task is to select around fifteen consumer product pairs for validation of the generated rules to determine if the ADA guidelines can be adapted for universal product design using the proposed framework.

The results of this research show promise in using the International Classification of Functioning, Disability and Health (ICF) lexicon to model user limitation. The actionfunction diagram provides a structured way to approach a problem in the early stage of design. The rules generated in this research translate to products having similar user-product interface.

DEDICATION

To my father

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Daniel A. McAdams for his guidance and support throughout the course of this research. I greatly appreciate the patience and positive attitude from Dr. McAdams. I would also like to thank my committee members, Dr. Julie Linsey, and Dr. Laura M. Stough. I appreciate their valuable input from time to time.

I wish to thank all my friends, family, and colleagues for their encouragement and support. I also wish to thank Matth Davis, Anosh Wadia, and Carlos De la Guardia for participating in the pilot study.

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1. INTRODUCTION

Forty-nine million individuals over the age of fifteen in America report having a disability [1]. The number of individuals with a disability constitutes almost 16% of the total population. As individuals age, they are more likely to acquire some disability, therefore, the number of disabled people is expected to increase in near future.

People with a disability are often an underserved segment of the population and an underused resource [2]. With the retirement of the Baby Boomer generation, the United States will loose twenty percent of its workforce by 2030 [3]. A national survey of consumer attitudes towards companies that hire people with disabilities shows that the aging population is an important group of potential employees [4]. One in four individuals over the age of 50 have a disability. Hence, to keep aging employees in service, the work environment must accommodate different abilities and limitations [3].

Disability is seen as a result of an interaction between a person and that person's environment and contextual factors [5]. Disability is the measure of how effectively one can perform in the environment as compared to others [6]. Viewing disability in the context of the built environment, a better design of this environment helps to reduce the disability faced by an individual. Ronald Mace coined the term Universal Design (UD) to describe the concept of equitable use of a product irrespective of the user's ability.

This thesis follows the style of Journal of Mechanical Design.

Universal Design is formally defined as, "*The design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design*" [7]. Broad practice of UD improves the inclusion of persons with a disability in both the consumption and production of goods and services.

Industries practice the concept of universal design either proactively with a view of creating easy-to-use human interfaces, or passively to comply with regulations to provide accessible products [8]. A line of products designed by OXO International has demonstrated a successful implementation of universal design [9]. In spite of higher costs, the OXO product line has been a commercial success among consumers both with and without a disability due to the product's overall ease of use. Success stories of universal products drive the motivation for improving design methodologies for universal design.

Owing to the growing awareness for universal design of products and environments, researchers have consistently strived to improve the design methodology for developing universal products. Significant efforts for UD are done at the Center for Universal Design at North Carolina State University, the University of Cambridge, the University of Buffalo, and the Trace R&D Center at University of Wisconsin-Madison [7, 10-12]. Nevertheless, the existing methods provide insufficient guidance for designers: designers demand more specific examples of, and methods for, good universal design [8].

The role and dynamics of government in the creation of legislation and civil infrastructure has contributed to a higher degree of universal access in architectural products and systems than in consumer products. There exists more knowledge, tools, and experience for universal architectural design than universal consumer product design. Though universal design of architecture is not a solved problem, there is a large and high quality set of resources available for architectural design [13-19]. The materials available include qualitative guidelines as well as quantitative parametric guidelines such as room layouts, counter heights, dimensional requirements for appropriate sight lines in large classrooms, and etc. The available guidance for universal architectural design surpasses what is available for universal product design.

This thesis reports the research efforts to transfer elements of the design knowledge and tools contained in universal architectural design methods to universal product design methods. Specifically, the focus is on elements of the ADA guidelines. The ADA has established formal guidelines for designing accessible architectural systems. These guidelines have achieved some level of success in providing accessibility to users with disabilities. Thus, the goal of the research is to determine if ADA guidelines can be re-adapted, or translated, such that they are applicable to product design.

The key focus of this research is on producing design knowledge and tools that can be used during conceptual, as well as other early stages of, design. Thus, my interest is on the early stages of the design effort, in which product functions are established and solution concepts are generated to meet the functional needs. An important goal is to understand the differences and similarities between typical and universal products in the early stages of the design effort. Thus, understanding the relationship between user activity, disability, and common and differing product characteristics is a crucial challenge of the research activity.

This research approach incorporates the International Classification of Functioning, Disability and Health (ICF) to formally describe user functions [5]. Similarly, the Functional Basis is used to describe product functions [20]. As a design representation framework for simultaneous product and user analysis, the research uses and extends actionfunction diagrams [21-23].

The following section reviews related literature and background on universal design. Section 3 explains the research approach with details such as the methodology for data extraction, an overview of the *American with Disabilities Act*, analysis of the product pairs, and the application of an association rule based algorithm. Section 4 details the trends observed from the analysis, observations from the rules generated, validation of the rules by comparing it with existing methods and applicability of rules for universal design of products. Section 5 concludes the thesis. The final section reviews the future scope of this research.

2. LITERATURE REVIEW

A comprehensive literature review of the research on universal design could fill several volumes. Here, I present a short overview of the relevant work. The following sub-sections summarize the background, universal design research, and the previous research efforts for universal design using a function based approach.

2.1 Background

Before presenting and discussing related work, some discussion of the terminology used to describe design for disability is appropriate. Within the community that serves persons with disabilities, multiple terms are used, including universal design, accessible design, inclusive design, design for all, and barrier free design, to indicate goods and services for persons with disabilities. In North America, the term ‘accessible design’ is perhaps the dominant term in architectural design for persons with a disability. Universal design is perhaps more closely associated with product design.

Universal design is the term gaining greater, and perhaps majority, acceptance. Also, the term universal design has been used to stress concepts of equity and solutions that simultaneously and equally serve consumers with and without a disability. The term ‘universal design’ is used throughout this thesis with recognition that often a truly universal design will not be achievable [24].

There is ongoing discussion about the precise meanings, overlap, and best use of the terms for design for disability. Though these discussions are important, they are not central to the efforts described here. With awareness that at times one of the other terms might be more accurate, I will use both the terms ‘accessible design’ and ‘universal design’ below as this discussion covers both architectural and product applications.

2.2 Universal Design

The landscape of universal design literature is vast and contains significant coverage of historical and social context. As an example, of the sixty-two chapters in *The Universal Design Handbook*, fifty-two chapters have significant coverage focused on the history of universal design, the rationale behind it, legal issues, documentation of workshops, or similar [25]. Notably, about twenty-four chapters provide descriptive guidelines and quantitative requirements for universal architectural design. Only about seven chapters contain guidelines, case studies, or other content that provides some insight into universal product design. The volume and emphasis of general universal design research publication activity mirrors the coverage in *The Universal Design Handbook*. Good overviews of universal design can be found in *The Universal Design Handbook* [25], *Handbook of Human Factors for the Older Adult* [26], and *Handbook of Human Factors* [27].

A team of researchers organized through The Center for Universal Design at North Carolina State University has compiled seven principles of universal design [28]. The seven principles of universal design are explained in detail in section 4.3.1. These principles have been well received by designers in a range of disciplines. Vanderheiden has developed a set of guidelines for the design of consumer products [10, 24]. These guidelines are explained further in section 4.3.2.

A team of researchers at the University of Cambridge has produced implementable results for universal product design [11, 29-33]. The focus of the Cambridge research group has been in modeling user groups, creating product assessment methods, and extending the needs of universal design to modern product design processes. The results of the Cambridge team are the most directly applicable to product design. Their effort has been primarily focused on the user and the design challenges of accommodating that user.

Housed in the Center for Inclusive Design and Environmental Access at the University of Buffalo is an active group of researchers with focus on universal design [34-37]. Though this group is focused on architectural design and comes from an architectural background, they have performed research on appliances and other applications that extend to product design.

Extensive literature is available for universal design of architectural systems. *The Accessible Housing Design File* suggests design features to make the home more universal [38]. Case studies of accessible buildings are available to the architects though the available literature is not well organized. The ADA is perhaps the most significant source of requirements and regulations for universal architectural design in the United States [39]. Further details of the ADA guidelines are summarized in section 3.2.

Universal design is an active research area. Nevertheless, fundamental work applicable to product design is still a sparsely populated space. What can be learned from a study of universal design practice and research is that the richness and clarity of universal design methods for architectural systems surpasses what is available for product design. This knowledge disparity serves as motivation to improve universal product design by translating what is known about architectural design to product design.

2.3 Previous Work on Similar Grounds

This section summarizes previous research efforts for universal design of consumer products using a function-based approach. Kostovich proposed the IED (Identify, Evaluate, and Determine) method to formally analyze the universal products [40]. Kostovich identified product pairs, evaluated the product pairs using a function based approach, and determined general design knowledge that can be used in product family design. The analysis was mainly focused on the consumer products. A new universal design database was created and used in conjunction with traditional conceptual generation tools such as morph matrices, function component and design structure matrices [40].

Cowen studied fourteen typical and universal product pairs and evaluated the differences between their activity diagrams and functional models. Further, using a data mining technique to generate association rules, around 29 interesting associative relations were extracted to design universal products [41]. Applicability of these rules was tested on the design of new universal products. Again, the set of products analyzed were mostly from consumer product category.

In this research, I propose to study the accessible architectural systems and translate the design guidelines to consumer products, using a function-based approach.

3. RESEARCH APPROACH

Within the overarching goal of improving universal product design, the specific goal of this research is to determine if the ADA guidelines for architectural design can be adapted to product design. Specific goals of this research also include determining if a function-based approach is able to anticipate a functional change that improves product accessibility. Further goals include the generation of user activity and product function association rules that can be applied to the universal design of products. Organization of this section is explained here.

Section 3.1 explains the methodology for extracting universal design features from the existing universal products. A user activity and product function framework is proposed for this translation using actionfunction diagrams.

The Americans with Disabilities Act is detailed in section 3.2. The product pairs selected for this study, categorized as architectural product pairs and consumer product pairs, are listed in section 3.3. The methodology for the extraction of rules explained in section 3.1 is applied for analysis of the ADA guidelines, the architectural products, and the consumer products.

Lastly, to extract association rules of the user-product interaction from the universal design features, a data mining technique is employed. Section 3.4 summarizes the algorithm for mining association based rules and its application to this research.

3.1 Methodology for Data Extraction

This section explains the methodology for the extraction of the specific design features that improve the accessibility of a universal product. A comparison between typical and universal products identifies these design features. Figure 1 depicts the approach used to identify the design differences between a typical and universal product.

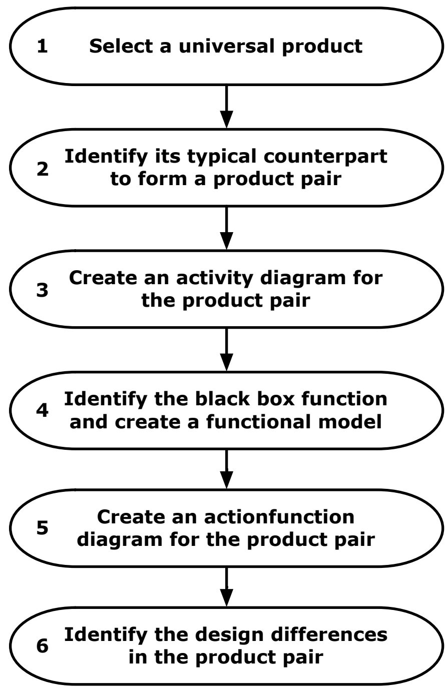


Figure 1. Sequence of the steps performed for extraction of the design differences between a universal product and its typical counterpart

As shown in Figure 1, the first step is to select a good representative universal product and the second step is to identify its typical counterpart to form a product pair. To perform the first two steps, section 3.1.1 explains the selection criteria for a universal product and the concept of a product pair. Once a universal product pair is selected for analysis, the third step is to model the user with reference to the product by creating an activity diagram for the product. Section 3.1.2 details modeling of the user with a disability. The fourth step is to identify the black box model and create a functional model for the product pair. Note that, black box function of a product is the greatest, overall function of the product [42]. Functional modeling of the product is explained in section. 3.1.3.

To gain insight into the interplay between product functions and user activities, the fifth step is to create an actionfunction diagram for the product pair. Section 3.1.4 explains the concept of actionfunction diagrams for modeling the user-product interface. The sixth step is to study the differences and similarities in a product pair by comparison of the actionfunction diagram for universal and typical product.

Systematic classification of the design differences in a product helps to organize the available information. The design differences to be identified in the last step are clarified in section 3.1.5. To represent the design differences on an actionfunction diagram, sections 3.1.6 discusses the representation scheme used in this thesis. Section 3.1.7 illustrates the methodology for data extraction with a case study of a universal bathtub.

3.1.1 Product Pair Selection Criteria

To begin with the study of universal products it is necessary to identify apt examples of universal design. This section explains the concept of a product pair and the selection criteria for a universal product.

Two products that provide the same overall functionality but differ in their level of accessibility are termed a product pair [21]. The more accessible, or universal, product better accommodates some user disability by introducing one or more design features that are not observed in the typical version. Figure 2 illustrates a utility cutter product pair. The Fiskars Rotary Cutter and the typical box cutter provide the similar function of paper and cardboard cutting but the Fiskars Rotary cutter has features that make it preferable for users with reduced hand functioning. The universal design features of the Fiskars Rotary cutter are an ergonomic handle for better grip, a circular blade that can cut in both the directions, and a push button to retract the blade.

Figure 2. A product pair of a Fiskars Rotary Cutter (above) and standard box cutter (below) [21]

In this research, product pairs are used for better understanding of universal design features leading to universal design guidelines or validation of the resultant guidelines. Initially, product pairs are studied to determine recurring themes in the features that differentiate universal products from typical products. These themes can then be formalized into design knowledge, rules, or guidelines. Subsequently, additional product pairs can be used to assess the validity of resultant design guidelines: when the universal design guidelines are applied to the typical product in the pair, is the suggested change consistent with the universal product in the product pair?

Specific characteristics of a product pair make it preferable for this research. Simply put, the better the universal product serves users with a disability and the more easily observed the design features are, the better the product pair is as a candidate for analysis and validation. Elaborating on these criteria further, in a good product pair, the universal one must overcome the limitation faced by a disabled user while using the typical product. Commercially successful universal products combined with a typical product to form a pair are good product pair candidates since they indicate a successful increase in product accessibility with acceptable, if any, increase in cost. Products consistent with a design specification mandated by law also indicate a good candidate product pair, as the legislation is focused at a high level of inclusion. In addition, the examples of universal design provided by researchers in this field can be used as a benchmark while selecting good product pairs.

Note that, a product termed as universal actually may not be the choice of every individual. Personal preference always plays a role, when a consumer selects one product from many available choices. Nonetheless, selection of universal products, in this research, does not account for personal style or satisfaction of the user. A product that includes larger group of user population is considered to be better. Moreover, a universal product that is universal in the sense that it has a broad range of applications, such as a universal wrench, does not constitute as an example of universal design.

3.1.2 Modeling the User with a Disability

A user with a disability might have difficulty in performing one or more activities performed by a user without a disability. Thus, user centric activity modeling is crucial to designing universal products. Building on notions of user centric design, this research specifically focuses on the interplay between user activity and product function. To create clear and repeatable representations of user activity, the research approach uses a formal method for user activity modeling. This modeling method, called an activity diagram, is described here.

An activity diagram is a network of high-level user activities encompassing the life cycle of a product from purchasing to recycling or disposal. Generally, the list of activities does not include design or manufacturing related activities. An activity diagram helps to gather customer needs in the initial phase of product design. The main objective of an activity diagram is to ensure that the designer is aware of the entire set of customer needs during the life cycle of a product. With admission that improving purchase or acquisition and disposal of a product can greatly include accessibility to a user with a disability, the user activities of purchase and disposal are not considered in the discussion here, for brevity. It is assumed that all the products are already installed and available for use.

Constructing an activity diagram for a product helps to visualize the body movements involved while using that product. Consider an example of a water fountain. The activities involved while drinking water from a fountain are positioning the body, reaching out a hand to push the button, and collecting water from the spout. A water fountain designed for a standing posture can be difficult to use for an individual with a lower limb disability: particularly, the difficulty is to perform the activity of ‘positioning the body'. In the context of the activity diagram, the disability can be viewed as a limitation to perform an activity.

A formal representation for describing the varied user activities improves consistency and communication amongst different designers. The International Classification of Functioning, Disability and Health (ICF), established by World Health Organization provides a standardized common language for the description of health and health-related states [5]. For user centric design, user activities can be modeled using ICF for repeatability of representation. Figure 3 shows the organization of the ICF. The classification is decomposed into parts, components, constructs, and domains and categories.

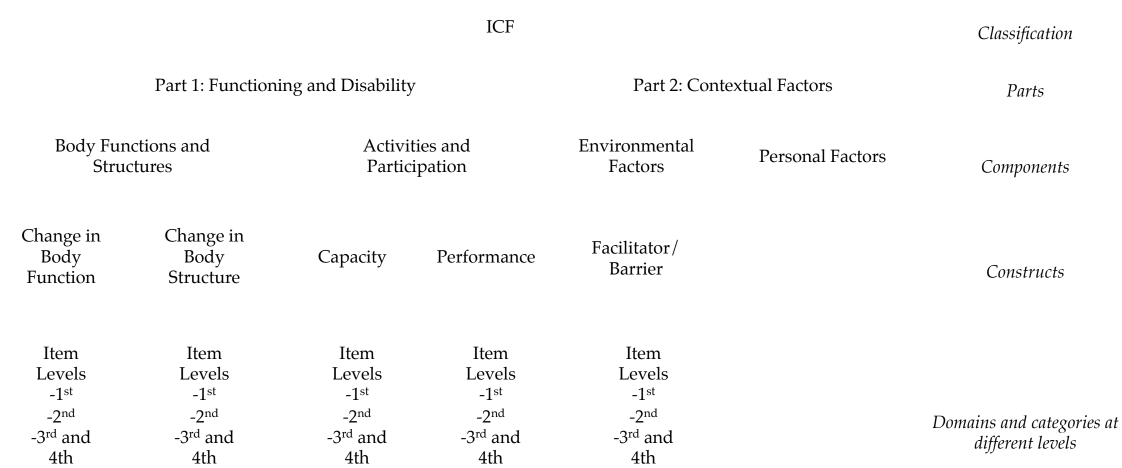


Figure 3. The structure and taxonomical organization of the ICF [5]

The ICF provides a systematic organizing scheme and coding rules for human functional ability and limitation. The general scheme is an alphanumeric code that categorizes the limitation according to the organization shown in Figure 3. The alphanumeric code is followed by a decimal point and additional digits used to further qualify details of a functional limitation. This scheme is illustrated in Figure 4.

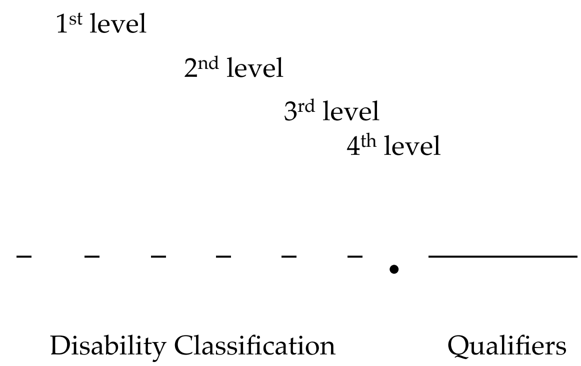


Figure 4. An illustration of the format for alphanumeric code using the ICF

The first digit on the left identifies the ICF *component*. The first digit is either *b* for body function, *s* for body structure, *d* for activities and participation, or *e* for environmental factors. The second digit from the left further categorizes the limitation with a number while the remaining elements provide a greater level of specificity or detail. The 3rd and 4th digits come as a pair.

For example, b7 is neuromusculoskeletal and movement related functions, where b750 to b789 cover movement functions; b750 is motor reflex functions, b760 is control of voluntary movements, b7601 is control of complex voluntary movements. In some cases, particularly for the classification of body structures, a 6th digit is provided for even greater classification and detail. Figure 4 illustrates how the coding builds up to 4 levels of detail. Generally, 2nd level precision (the first four digits in Figure 4 above) is used in practice.

Qualifiers are placed to the right of a decimal point following the 6th digit as shown in Figure 4. For example, if body function (*b)* is being categorized, a single digit right of the decimal point is used to represent the level of impairment. The qualifiers are designated as none (0), mild (1, 5%-24%), moderate (2, 25%-49%), severe (3, 50%-95%), complete (4, 96%-100%), not specified (8), and not applicable (9). In the case of activity limitation (*d*) qualifiers are used to describe limitations both without and with assistance. However, in this research the qualifiers are not employed for user activity representation and reserved for future work.

The ICF has been used in a range of health applications for correlating the specific links between conditions and function limitations [43]. It has been used to explore connections between functional limitations and high level participation such as working [44]. One of the important applications of ICF is the statistical measurement of disability by the United States Census Bureau [1]. Numerous other applications include its use as a framework for collecting and analyzing health data, to identify patient problem areas, and to evaluate the quality and results of patient care [45].

Specifically using the ICF as user representation lexicon for formal universal product design methods is not well known. In this research, the activities and participation component (*d*) is exclusively used. Based on an initial review, ICF activities and participation appears to suitably describe the user activities related to consumer products. Despite that, the ICF representation requires some assumptions while using to describe complex human functioning.

Formally modeling user activity with the ICF, particularly in the context of function based product design, is still a developing method. Some interpretation is required when modeling user activity. For example, the activity *releasing (d4403)* is defined as the activity of dropping something on the floor causing it to fall or change the position. In the activity diagrams, it is assumed that a user releases objects after the activities of *grasping (d4401), pulling (d4450), turning (d4453), or carrying in hand (d4301)*. In cases when the hand is to be repositioned to perform another set of tasks, the user activity *reaching (d4452)* is repeated in the activity diagram. In addition, the ICF user activity of *maintaining body position (d415)* is used to model a sitting or standing posture of the user.

Additionally, some modeling judgment is used when modeling expected user activity and product function interaction. The activity of *grasping (d4401)* is not needed when the activity can be performed with a closed fist. For example, a round doorknob needs *grasping (d4401)* and *turning (d4453)*, while lever type knob allows *pushing (d4451)* with a closed fist.

3.1.3 Modeling the Product

To represent product function, the Functional Basis and the associated flow based functional modeling methodology are used [20, 46]. The Functional Basis has achieved significant evaluation and acceptance as a repeatable method for representing product function [47-53]. Good summaries of discussions on how to use the flow based modeling method can be found in [54].

For brevity, human energy flow is not shown in the function structure. It is assumed that human energy is utilized to perform a task wherever human body is involved. Other forms of energy are explicitly mentioned. To be precise, ‘Human’ and ‘Hand’ are used specifically. ‘Human’ is used if the entire human is involved in the activity, for example, entering or exiting bathtub. When the user performs a task with upper limb or hand, it is represented as ‘hand’. For instance, the operation of a lever or switch involves hand and arm use.

3.1.4 Modeling the User-Product Interface

The key design elements analyzed in this research are the user activity, the corresponding product function, and the change in the product required to accommodate the user. Thus, attention is mainly focused on the representation of product function, user activity, and the interaction between them.

The formal representation used to analyze the interplay between user and product is the actionfunction diagram [21]. An actionfunction diagram is an activity diagram and a functional model combined into a single representation. Figure 5 shows an actionfunction diagram. In an actionfunction diagram, dashed boxes represent user activities with related product functions contained within each activity.

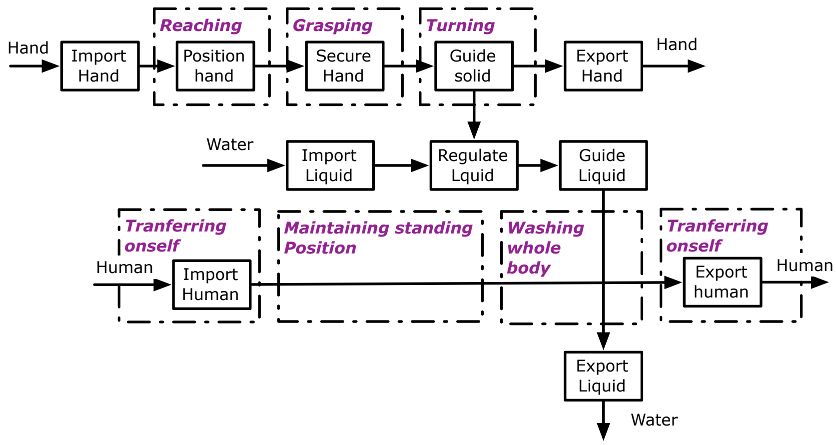


Figure 5. An illustration of an actionfunction diagram. Dashed boxes represent user activities with related product functions contained within each activity. This actionfunction diagram is for a typical bathtub discussed in section 3.1.7.

Actionfunction diagrams highlight those functions of a product in which the user is involved. Functions that interface with the user have the greatest impact on improving the accessibility of a product. By carefully comparing the actionfunction diagram of a universal product and its typical counterpart, one can observe the change in the product function that accommodates a user with a disability. Thus, an actionfunction diagrams present a framework for designing with a high degree of focus on product and user interaction. Here, that focus facilitates universal design. Additionally, the framework allows for analysis of product and user interaction early in the design process.

3.1.5 Design Difference Classification

Previous universal design research indicates that in many cases the difference between universal and typical products in a product pair is minimal: differences between the products are often subtle and a significant portion of the components are essentially identical [21]. The design differences that do exist can be classified as parametric, morphological, or functional. These differentiating concepts are clarified here.

A *parametric* difference between a typical and universal product refers to two products that could be described with the same parameterization, but have a differing value for some parameter. Parametrically different products exhibit common detailed functionality, solution principle, and form. A sloped ramp entrance can be used to illustrate a parametrically different product pair. For example, to be accessible, the slope of the ramped entrance should not be greater than 1:15 [39]. A ramp with steeper slope would be a typical product in this case. Figure 6 illustrates a parametric difference between two architectural systems that provide the same overall use, detailed functionality, and morphology. The steep ramp on left is inaccessible while the ramp on right is accessible as its slope is less than 1:15.

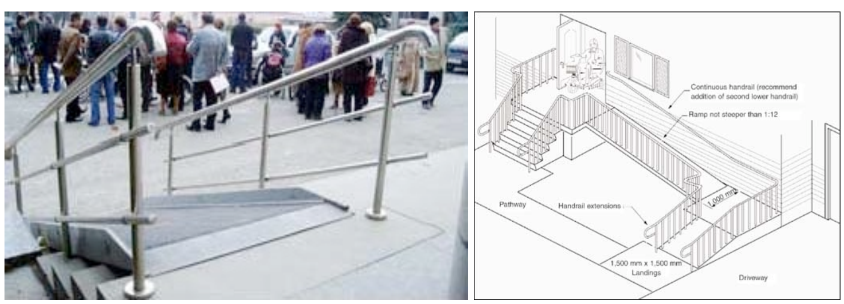


Figure 6. A steep ramp with slope greater than 1:15 illustrating an inaccessible entrance (left) [55] and a parametric difference in the ramp slope to create a gradual ramp as an accessible entrance (right) [10]

A *morphological* difference refers to two products that share the same detailed functionality but do not clearly exhibit a similar parameterization. The two products exhibit a different physical solution principal, form, or geometric topology. Again, using a building entrance as an example, a ramp and a stairway can be used to illustrate a morphologically different product pair. Figure 7 shows an inaccessible entrance based on a step morphology (left) and an accessible entrance using a ramp morphology (right).

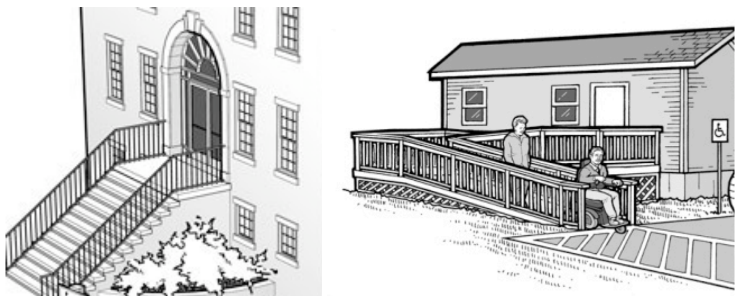


Figure 7. An inaccessible building entrance based on a stair morphology (left) [7] and an accessible building entrance (right) [56] based on a ramp morphology illustrating a morphological difference from the stair

A functionally different product pair indicates the addition or deletion of a product sub-function, or the change of some product sub-function, to improve its accessibility. The addition of a function may be in addition to other parametric or morphological product differences. A wheel chair lift in addition to, or in place of, stairways at a building entrance is an example of a functional difference. The lift adds a new set of functions to make the building entrance accessible. Figure 8 shows an inaccessible stairway (left) and illustrates a functional change through the addition of a wheel chair lift to make a stair entrance accessible (right).

Figure 8. An inaccessible stair step (left) [39] and an accessible building entrance (right) [57] illustrating a functional difference from the stair based entrance

3.1.6 Representation Scheme

Actionfunction diagrams depict parametric, morphological, functional differences between a product pair. In the diagram, a parallelogram, an oval, and a diamond shape represent parametric, morphological, and functional product differences, respectively. Consistent with the Functional Basis and associated flow based functional modeling methodology, a solid line, a dotted line, and a dashed line represent the material, energy, and signal flows respectively [54, 58]. Figure 9 shows the legend for actionfunction diagrams.

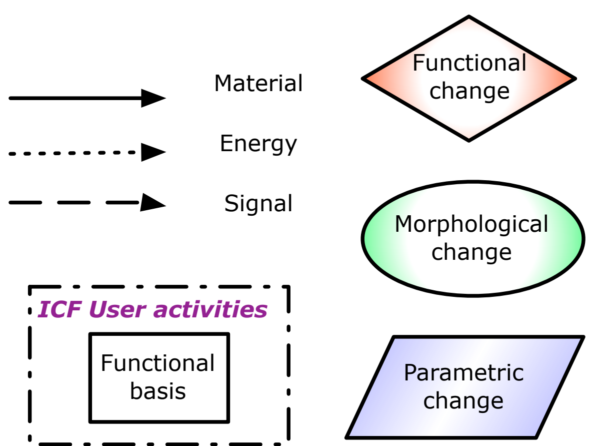


Figure 9. Legend used in actionfunction diagrams

3.1.7 Case Study

To illustrate and detail the analytical comparison process, the research approach as applied to a bathtub is discussed here. Figure 10 shows examples of a typical and a universal bathtub. Design elements that differentiate the universal tub from the typical tub include grab bars, an adjustable seat, a lowered sidewall, and a single lever water control located toward the outer edge of the bathtub.

Figure 10. A typical bathtub (left) and a universal bathtub (right) [59, 60]

Figure 11 shows an activity diagram for the bathtub with user activities expressed in the ICF lexicon and taxonomy. The activity of getting in and out of the bathtub is modeled by the ICF activity of *transferring oneself* (*d420*). The second user activity is *maintaining body position* (*d415*). The user activity of operating water controls is modeled using *reaching* (*d4452*), *grasping* (*d4401*), and *turning* (*d4453*). The activity diagram is completed with *washing whole body* (d5101) and *transferring oneself* (d420). In the case of bathtub, the activity diagram for a typical and universal bathtub remains the same.

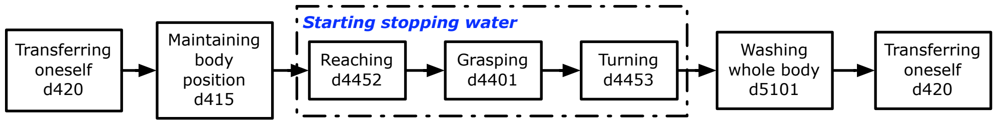


Figure 11. An activity diagram for a bathtub

During the activity modeling effort, I moved back and forth between different levels within the ICF. For example, *d415* and *d4452* are at different levels of specification, or fidelity, within the ICF taxonomical structure. My modeling goal was to model the user activity as precisely as the ICF lexicon allows rather than to use a consistent level within the ICF.

Figure 12 shows the actionfunction diagrams for both the typical and universal bathtub. The intermediate step of creating a Function Structure is not illustrated here. These actionfunction diagrams illustrate the manner in which the representation scheme allows comparison between a product pair with a focus on the interplay between user activity and product function. As can be seen in the actionfunction diagram shown in Figure 12, a number of product functions do not interact with a user activity at all: the functions are internal to the product. For the bathtub, these are import, regulate, guide, and export liquid. Similarly, the import and export hand functions were included as product functions for continuity, but were not explicitly associated with a user activity to simplify and focus the analysis.

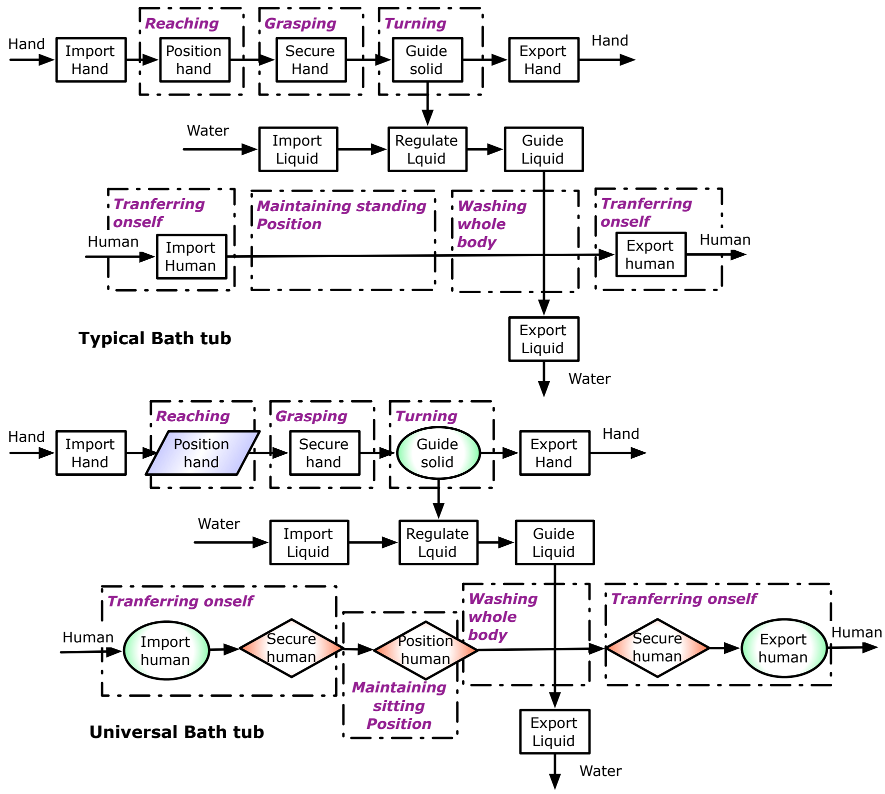


Figure 12. Action-function diagrams for a typical (top) and a universal bathtub (bottom)

Access to the water spigot is modeled by the user activity of *reaching* (*d4452*) and the product function of *position hand*. In contrast to the typical bathtub, the water controls in the universal bathtub are offset from the center, such that a user can also operate it while standing outside the bathtub. Relocation of the water controls is a parametric change.

To accommodate the user activity of *turning* (*d4453*) and provide the product function of *guide solid*, water controls in the universal bathtub are single lever handles that can be operated with one hand. The single handle solution is a morphological change from the two round knobs in the typical bathtub.

To provide the *import human* function, which interacts with the activity of *transferring oneself* (*d420*), the universal tub simply provides a lowered sidewall cutout. The lowered sidewall cutout is built into the universal bathtub for easier entry and exit. The sidewall cutout is a morphological change.

To better accommodate disabled users, grab bars are installed in the universal bathtub for support as one climbs in and out of the bathtub. These grab bars represent a functional change, specifically the addition of a *secure human* function, to support the user activity of *transferring oneself* (*d420)*.

To better support the user activity of *maintaining body position* (*d415*)*,* an adjustable seat is added to the universal bathtub. The adjustable seat provides a *position human* function to the product and thus is a functional change between the typical and universal bathtub. Note in this case, the user activity slightly changed from *maintaining standing position* (*d4154*) to *maintaining sitting position* (*d4153*). Table 1 summarizes the results of the analysis for the typical and universal bathtub comparison.

To know if the ADA guidelines can be translated to universal product design, a detailed study of the ADA is considered crucial. The following section explains the analysis of the ADA guidelines.

Table 1. A summary of design differences between a universal and typical bathtub

		Design Feature		
Activity	**Function**	**Typical**	**Universal**	**Design Difference**
n/a	Import Hand	n/a	n/a	n/a
Reaching	Position Hand	Central location	Offset location	Parametric
Grasping	Secure Hand	Handle	Handle	n/a
Turning	Guide Solid	Two round knobs	Single lever control	Morphological
n/a	Export Hand	n/a	n/a	n/a
n/a	Import Liquid	n/a	n/a	n/a
n/a	Regulate Liquid	n/a	n/a	n/a
n/a	Guide Liquid	n/a	n/a	n/a
Transferring Oneself	Import Human	Tub wall	Sidewall cutout	Morphological
	Secure Human	none	Grab bars	Functional
Maintaining Sitting Position	Position Human	none	Adjustable seat	Functional
Washing Whole Body	n/a	n/a	n/a	n/a
Transferring Oneself	Secure Human	none	Grab bars	Functional
	Export Human	Tub wall	Sidewall cutout	Morphological
n/a	Export Liquid	n/a	n/a	n/a

3.2 Americans with Disabilities Act (ADA)

The *Americans with Disabilities Act* (ADA) was signed in 1990 as an attempt to eliminate structural and attitudinal barriers faced by individuals with disabilities. Over the last two decades, the ADA has achieved considerable success in removing barriers from architectural systems and improving access to public facilities. This section provides an overview of the ADA. Note that the ADA Amendments Act of 2008 is not considered for the study. The discussion is limited to original act signed in 1990.

Each design guideline of the ADA is intended to reduce the exclusion of persons with a disability. For instance, providing ramps in addition to stairways allows a wheelchair user access to a building. Significant effort and research has been devoted to expanding, clarifying, and improving the concepts contained within the ADA [61-64].

Most of the ADA guidelines and related discussion focus on built-in, or permanent, elements of buildings. Within this focus, the ADA guidelines cover a broad spectrum of details including dimensions of spaces for easy maneuvering of a wheelchair, seat height, character size of signage, strength and frequency of an alarm signals, and requirements of hearing aid compatible audio systems in an auditorium.

Not all guidelines suggest clear or specific design changes; for instance, the ADA guideline of *'accessible toilet stalls shall be on an accessible route'* is an example of a high-level design requirement. Specific guidelines about how to achieve accessibility include both general qualitative guidelines and specific design guidelines. The guidelines such as *'revolving door should not be the only means of passage'* serve as an example of the qualitative guidelines. The specific allowable dimensions (slope, width, and surface texture) of an entrance ramp serve as an example of the quantitative design guidelines. Primarily, the quantitative guidelines are analyzed in this research.

Altogether, the ADA comprises ten sections and an appendix. Section 1, 2, and 3 of the ADA explains the purpose, scope, and miscellaneous instruction and definitions related to the ADA. Section 4 covers basic building spaces and elements. The ADA specifies accessibility regulations for various facilities including restaurant and cafeterias, medical care facilities, business and mercantile, libraries, accessible transit lodging, and transportation in sections 5 through 10. Sections of 5 through 10 of the ADA are built on the basics specified in section 4.

Section 4 of the ADA discusses design details of the accessible elements and spaces; hence, it is considered most relevant to this research. ADA guidelines often encompass the dimension and specifications of accessible elements such as parking spaces, entrances, passages, ramps, stairs, handrails, elevators, windows, and doors. Section 4 of the ADA also includes specification and installation requirements for automated teller machines, telephones, alarms, signage, controls, and drinking fountains. In addition, space configuration of building elements such as toilets, urinals, lavatories, bathtubs, shower stalls, sinks, water closets, storage, assembly areas, seating and tables, and fitting rooms are documented in section 4.

Detailed analysis of section 4 of the ADA develops an understanding of design features that improve accessibility. The ADA guidelines are well organized for direct implementation. Each guideline is expressed at a general level such that they are not product dependent. Due to the general, or product independent, nature of the ADA guidelines, a product specific functional model is not created as part of the methodology to extract user activity and function based guidelines from them. Instead, each guideline can be viewed as a direct rule and analyzed further.

The design features suggested by the ADA can be traced back to the related user activity. Then, it can be determined how the design is modified to aid an activity that a disabled user can not perform with some typical design. For example, a ramped building entrance accommodates a user with limitations in the activity of walking. In addition, the product function and the type of design change, namely, parametric, morphological, or functional, advocated by the guideline to the product function are recorded in the same manner as if they were extracted from a specific product instance.

A few assumptions are necessary for systematic classification of the ADA guidelines. The assumptions are illustrated here using an example of an *elevator*. Table 2 illustrates how the information from ADA guideline *4.10 - Elevators* is transformed into design knowledge. The first column, *specifications,* in Table 2, lists the ADA guideline. The second column, *comment,* gives a short description of the ADA guideline. The next four columns specify the user activity, ICF code of the activity, the product function, and the type of change. Section 4.10.3 of the ADA lists following requirements for a *Hall Call Buttons* inside an elevator [39].

> Call buttons in elevator lobbies and halls shall be centered at 42 in (1065 mm) above the floor. Such call buttons shall have visual signals to indicate when each call is registered and when each call is answered. Call buttons shall be a minimum of 3/4 in (19 mm) in the smallest dimension. The button designating the up direction shall be on top. Buttons shall be raised or flush. Objects mounted beneath hall call buttons shall not project into the elevator lobby more than 4 in (100 mm).

Three main requirements of the *Hall Call Buttons* specified are 1) location of the buttons, i.e. distance above the floor, 2) a visual signal to indicate the call status, and 3) dimension, configuration, and installation specification of the buttons itself. In a typical elevator, hall call buttons might be inaccessible to a user on a wheelchair if they are located too high above the ground level. A parametric change to the product function-

position hand makes the user activity - *reaching (d4452)* more inclusive. The design requirement related to the visual signal flow is a functional change, as it adds the function of *indicating status* to aid the activity of user *seeing functions (d210)*. Dimensions and specifications of the buttons are classified as a parametric change to the product function *guide solid* such that the activity of *manipulating (d4402)* also includes users with reduced hand functioning.

Table 2. Illustration of the design changes suggested by section *4.10 - Elevators* of the ADA; with associated user activities, product functions, and design changes

Specifications	Comment	User activity	ICF	Product Function	Change
4.10 Elevators					
General	n/a				
Automatic Operation	Auto leveling	n/a	n/a	Position solid	Functional
Hall Call Buttons	Location	Reaching	d4452	Position Hand	Parametric
	Button dimensions	Manipulating	d4402	Guide Solid	Parametric
	Visual signals	Seeing functions	b210	Indicate Status	Functional
Hall Lanterns	Location	Reaching	d4452	Position Hand	Parametric
	Visual signals	Seeing functions	b210	Indicate Status	Functional
Raised and Braille Characters	Dimensions	Communication-receiving written messages	d325	Indicate Status	Parametric
Door Protective and Reopening Device	Auto opening	n/a	n/a	Guide Solid	Functional
	Dimensions of open way	Moving around within buildings other than home	d4601	Import / Export Human	Parametric
Door and Signal Timing for Hall Calls	Time for answering call	n/a	n/a	Import / Export Human	Parametric
Door Delay for Car Calls	Time for remaining open	n/a	n/a	Import / Export Human	Parametric
Floor Plan of Elevator Cars	Dimensions	Maintaining a body position	d415	Position Human	Parametric
Floor Surfaces	Section 4.5 of ADA				
Illumination Levels	Min light intensity at call buttons	Seeing functions	b210	Indicate Status	Parametric
Car Controls	Location	Reaching	d4452	Position Hand	Parametric
	Button dimensions	Manipulating	d4402	Guide Solid	Parametric
	Visual signals, tactile, Braille	Communication-receiving written messages	d325	Indicate Status	Functional
Car Position Indicators	Audible signal	Communication-receiving written messages	d310	Indicate Status	Functional
	Visual signals	Communication-receiving written messages	d325	Indicate Status	Functional
Emergency Communications	Qualitative				

All the building elements specified in section 4 of the ADA are analyzed and documented in Appendix A. General observation forms the ADA guidelines are listed here. Twelve percent of the guidelines are qualitative and cannot be analyzed. Fifteen percent of the guidelines give general directions for accessibility; these are tagged as not applicable (n/a). Next, thirteen percent of the guidelines are either repetitive as they refer to other section of the ADA for details, or reserved for future update. Almost 40% of the guidelines do not suggest any design specification.

Thus, out of total 230 guidelines, only 142 are relevant for this research. Relevant guidelines are extracted and analyzed using association rule based algorithms, results of which are discussed in section 4.1.1. Preliminary analysis of the trends in ADA guidelines, shows that of the total design changes suggested by ADA, 13% are functional, 10% are morphological, and 77% are parametric.

Table 3 and Table 4 show the frequency of occurrence of the common user activities and product functions respectively from the analysis of section 4 of the ADA. The user activity *moving around (d460)* is the most frequent, followed by the activity *reaching (d4452)*. The product function *Import or Export Human* occurs in 35 % of the cases, while the product function *Position Hand or Human or Solid* is the next most frequent with an occurrence of 27%. Explanation of some examples of parametric, morphological, or functional change in the ADA guidelines follows.

The most commonly observed user-product interface is between the function- *import* or *export human* and the activity *moving around (d460).* A simple parametric change introduced by appropriate dimensioning of the building passages makes the activity *moving around* inclusive even for the wheelchair users. In addition appropriate turn around space for a wheelchair needs to be provided.

Table 3. Frequency of occurrence of the common user activities in the analysis of ADA guidelines

User Activity	ICF	Frequency of occurrence %
Moving around	d460	36
Reaching	d4452	12
Manipulating	d4402	10
Hearing functions	b230	3
Seeing functions	b210	6
Grasping	d4401	5
Communicating	d310-d329	6

Table 4. Frequency of occurrence of the common product functions in the analysis of ADA guidelines

Product Function	Frequency of occurrence %
Import / Export Human	35
Position Hand/ Solid/ Human	27
Secure Human/ Hand	7
Guide Solid	16
Indicate Status	5

Usually, functional changes to the product function *indicate status* reduces exclusion of a user with reduced vision or hearing. Activities in ICF lexicon used to model limitations in vision or hearing are c*ommunicating with - receiving - written messages (d325)* or *communicating with - receiving - spoken messages (d310)*. To include the users with reduced vision or hearing, the ADA guidelines suggest that, important information must be provided in more than one form of communication such as text, voice, symbolic, tactile, visual signal, or Braille.

As specified in section 4.24 of the ADA, assembly, or gathering, areas require types of listening systems, which are compatible with hearing aids or other assistive devices. Listening systems with magnetic induction loops are morphologically different from listening system with infrared technology, since they provide the same overall use but differ in the solution principle. To sum up, the installation of listening systems, which is compatible with assistive devices instead of a non-compatible system, is an example of morphological change.

3.3 Product Pairs for Analysis

After studying the ADA design guidelines for improving accessibility in section 3.2, a comparative discussion of more product pairs is considered in this section. Product pairs are selected based on the product pair selection criteria, which is explained in section 3.1.1. Product pairs selected for analysis are classified into two categories 'architectural product pairs' and 'consumer product pairs' based on the size and shape relationship between the user and a product. Classification also depends on the control volume around the product considered for constructing and analyzing the functional models.

In the context of the product and user analysis here, a control volume defines the physical boundaries around the product considered for the creation of a functional model. For instance, for a toilet, not only is the seat height and flush controls important but also the space around the toilet. The space around the toilet is crucial for user approach and exit and is thus included in the control volume of analysis. In contrast, space around the scissors is not included in the control volume of user and product analysis. Generally, Architectural products encompass the space around the product while consumer products do not.

The design differences between the products pairs are extracted using the methodology for data extraction explained in section 3.1. These design differences are then listed along with the related user activity, products function, and the design change. The following sub-sections explain the architectural and consumer product pairs in detail.

3.3.1 Architectural Product Pairs

The concept of accessible design is extended to personal housing, more broadly known as independent living, universal home design, or smart homes [13-19]. *The Accessible Housing Design File* lists the design changes that ameliorate accessibility of a personal space [38]. ADA guidelines mandate regulations for public building spaces. Accessible architectural products are basically a personal choice and not regulated by any law. They improve the quality of living for disabled and aging population.

For architectural products, the size and shape relationship between the user and a product, are similar to the ADA guidelines. However, in terms of innovative design the architectural products are a step ahead of ADA. The universal architectural products taken from the Accessible Housing Design File [38] and studied here are a bathtub, a range cook top, a microwave oven, a conventional oven, a dishwasher, a refrigerator, a kitchen cabinet, a bedroom closet, and a kitchen drawer. Some of the architectural products selected for study are listed in Appendix B. About 30 design features that improve accessibility are found in these architectural products. These features are listed in Table 5.

Table 5. Design features improving the accessibility in architectural products along with the related user activities, product functions, and type of change

Universal Design Feature	User Activity	Product Function	Change
Space in front of microwave	Carrying in hands	Position Solid	Parametric
Rack at counter height - Microwave	Carrying in hands	Position Solid	Parametric
Raised dishwasher	Carrying in hands	Position Solid	Parametric
Knee space - wash basin	Maintaining body position	Position Human	Parametric
Knee space below sink	Maintaining body position	Position Human	Parametric
Lowered sink height	Maintaining body position	Position Human	Parametric
Knee space below cook top	Maintaining body position	Position Human	Parametric
Knee space besides oven	Maintaining body position	Position Human	Parametric
Dishwasher besides sink- knee space	Maintaining body position	Position Human	Parametric
Counter- height	Maintaining body position	Position Human	Parametric
Dispenser switch in front - Sink	Reaching	Position Hand	Parametric
Front mounted controls- Cook top	Reaching	Position Hand	Parametric
Raised oven	Reaching	Position Hand	Parametric
Controls in front	Reaching	Position Hand	Parametric
Long Handles- Refrigerator	Reaching	Position Hand	Parametric
Space between sink and dishwasher	Reaching	Position Hand	Parametric
Side by side refrigerator	Reaching	Position Hand	Parametric
Bedroom closet- shelf height	Reaching	Position Hand	Parametric
Overhead Cabinets- height	Reaching	Position Hand	Parametric
Drawers- low sides	Seeing	Indicate status	Parametric
Floor space for parallel approach	Moving around	Import / Export Human	Parametric
Floor space - Cook top	Moving around	Import / Export Human	Parametric
Bedroom closet -space	Moving around	Import / Export Human	Parametric
Control knob with lever handle	Manipulating	Actuate Signal	Parametric
Touch buttons - Microwave	Manipulating	Actuate Signal	Morphological
Low side cut wall -Bathtub	Transferring oneself	Import / Export Human	Morphological
Single lever faucet - Sink	Grasping and Manipulating	Guide Solid	Morphological
Push button for opening door Microwave	Grasping and Manipulating	Guide Solid	Morphological

Of the total design changes found, 15% are morphological, and the rest are parametric. Recall, a morphological change is one that replaces an existing component with a different morphology or working mechanism that better accommodates a user with a disability. Half of the morphological product changes actually result in, or accommodate, a change in user activity. For example, the user activities of *grasping* (*d4401*) and *manipulating* (*d4402*) related to the *guide solid* function of a toilet are replaced by the user activity of *pushing (d4451)* through a morphological design change from a flush lever to a push button. Through this morphological change, not only are the numbers of user activities reduced, but *grasping* (*d4401*), which is a *fine hand use* (*d440*) activity, is also eliminated. Note that, the substituted user activity of *pushing (d4451)* falls under the *hand and arm use* (*d445*) of the ICF taxonomical classification.

Parametric changes identified in the study primarily involved configuring the elements of a product for gross user access. For example, products are reconfigured to allow knee space under a counter or turn around space near a toilet for a user in wheel chair. The change made to allow gross user access is clearly seen in the thirty percent of the parametric changes. These changes involved reconfiguration of space around the product to accommodate *maintain body position (d415)* activity and the *position human* function. For 38% of the parametric changes, the product function modified is *position hand* related to a user activity of *reaching* (*d4452*). Again, this parametric design difference supports gross user access. As an example, Figure 13 shows the accessible range of reach for a user's hand as specified by ADA guidelines and applied to the universal architectural products. The object to be reached must be located within this range.

The user activity *walking short distances* (*d4500)* and product function i*mport* or *export human* combination constitutes 12% of parametric changes. Again, these design changes provide adequate approach space for wheel chair users. Not all parametric changes are intended to improve gross user access. The parametric change in response to the *carrying in hands* (*d4301*) activity and *position solid* function combination provides intermediate space to position hot or cold objects in the kitchen while transferring them. These changes make up 12% of the parametric changes.

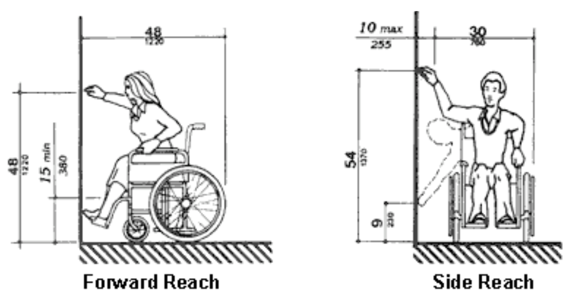


Figure 13. An example of a parametric ADA guideline that improves reach accessibility for a wheel chair user is applied to the universal architectural products [39]

3.3.2 Consumer Product Pairs

As a preliminary check of the applicability of the rules observed from the ADA to the consumer product domain, a few consumer product pairs are analyzed. The product pairs studied in this section are known examples of universal design and improve comfort and access for the user.

The products included from the consumer product category are a toilet seat, a recliner, an arm chair, a food storage box, a cabinet, a touch start faucet, perceptible controls, an automobile ingress system, a chopping bowl, a kettle, a power opened door, a television remote, a telephone, scissors, pruners, a can opener, and a box cutter. In general, the products considered are mechanical devices. Computer and information technology (IT) products are not included in the set analyzed. The consumer products selected for study are listed in Appendix C. Around 30 universal design features observed in the selected consumer products are listed in Table 6. In the consumer product's category, the functional, morphological, and parametric change occurs with the same frequency.

For thirty percent of the functional changes, the *guide human* function in the lifting mechanism aids the activity of *sitting (d4103).* Also, a ramp in PT Cruiser *guides human* while *transferring oneself (d420)*. Again in the PT Cruiser, the adjustable height feature add the function of *position human* to aid the activity *maintain body position (d415)*. Forty percent of the functional changes eliminate the activities of *manipulating (d4402)* or *pushing (d4451)* by addition of a motion sensor to operate the device with external power.

In 70% of the morphological changes to the consumer products, *guide solid* function is morphologically changed to make a user activity like *manipulating (d4402), grasping (d4401),* or *twisting (d4453)* easier. Morphological changes seem to have the maximum scope for innovation.

Table 6. Design features improving the accessibility in the consumer products along with the related user activities, product functions, and type of change

Universal Design Feature	User Activity	Product Function	Change
Lifting mechanism - Recliner	Sitting	Guide Human	Functional
Lifting mechanism - Toilet seat	Sitting	Guide Human	Functional
Lifting mechanism - Arm chair	Sitting	Guide Human	Functional
Ramp for transferring- PT Cruiser	Transferring oneself	Guide Human	Functional
Adjustable height - sink	Maintaining body position	Position Human	Functional
Universal Cabinet- adjustable height	Maintaining body position	Position Human	Functional
Power door at entrance	Pushing	Guide Solid	Functional
Auto faucet- Sink	Manipulating	Guide Solid	Functional
Touch start faucet- Sink	Manipulating	Guide Solid	Functional
Auto flush - Toilet	Manipulating	Guide Solid	Functional
Electric rotor- can opener	Grasping and Twisting	Guide Solid	Functional
Spring open- scissors	Manipulating	Guide Solid	Morphological
Easy blade open and close	Manipulating	Guide Solid	Morphological
Copco Chopping bowl	Manipulating	Guide Solid	Morphological
4 link mechanism - pruners	Grasping	Guide Solid	Morphological
Gas pedal in hand- Ford Focus	Pushing- lower extremity	Guide Solid	Morphological
Rotary blade- cutter	Pulling	Guide Solid	Morphological
Voice activated dialing	Manipulating	Actuate Signal	Morphological
Perceptible controls	Communicating-receiving	Indicate status	Morphological
Gull wing door - PT cruiser	Transferring oneself	Import / Export Human	Morphological
Driver side space - Ford Focus	Transferring oneself	Import / Export Human	Parametric
Ergonomic handle - cutters	Grasping	Secure Hand	Parametric
Ergonomic handle - scissors	Grasping	Secure Hand	Parametric
Ergonomic handle - can opener	Grasping	Secure Hand	Parametric
Ergonomic handle - pruners	Grasping	Secure Hand	Parametric
Ergonomic handle - remote	Grasping	Secure Hand	Parametric
Kettle- Large holding handles	Grasping	Secure Hand	Parametric
Large buttons on remote	Manipulating	Secure Hand	Parametric
Large tabs on Tupperware	Manipulating	Secure Hand	Parametric

Other instances of morphological changes include voice-activated dialing, perceptible controls, and gull wing doors. In voice activated dialing, a user can speak to make a call instead of dialing buttons. Perceptible controls of a device provide not only a visual feedback but also a tactile feedback through raised characters. The gull wing door of a PT Cruiser opens upwards instead of sideways, thus, allowing more space for *transferring oneself (d420)* in or out of an automobile. An accessible Ford Focus illustrates a contrasting design change. In the Ford Focus, a parametric increase in driver side space makes the activity of *transferring oneself (d420)* easier. Ninety percent of parametric changes are related to *secure hand* function, where either *grasping* (*d4401*) activity is improved by ergonomic design of handles or *manipulating (d4402)* activity is aided by provision of large buttons and tabs.

Sections 4.1.2 and 4.1.3 analyze and discuss the design features of architectural and consumer product. The following section explains the algorithm used to extract association rules based on the design changes observed.

3.4 Association Rule Based Algorithm

This section gives a brief overview of the algorithm for mining association based rules and its application to my research. An algorithm to generate rules based on design differences extracted as explain in section 3.1 is helpful. The basic requisite of algorithm in my research is to expedite the process of rule generation and allow multiple iterations with various combinations. The manual rule generation process consist of analyzing the entire data set and find recurrently occurring set of user activity, product function, and the type of change along with its frequency of occurrence. The process of rule extraction gets cumbersome for large data sets such as in case of ADA guidelines. In my research, association rules based algorithm is used. The concept of data mining technique is explained further.

Bar code technology enabled massive storage of sales data, with details like transaction date and items bought. Such a collection of data is known as *basket data*. Analysis of basket data is helpful for cross marketing, catalog design, promotional offers, and determining store layout. Hence, data mining techniques are developed to extract association rules from large datasets. The algorithm used for mining association rules here was developed by Agrawal in 1993 [65]. Agrawal explains the concept of mining association rules in [65]. This section summarizes a part of the explanation for association rule learning [65].

$I = \{i_1, i_2, ..., i_m\}$	Set of items	
D	Set of transactions	
T	Each transaction	where, $T \subseteq I$
TID	Transaction identifier	
$X \Rightarrow Y$	Association rule	where, Antecedent, $X \subseteq I$ Consequent, $Y \subseteq I$, And $X \cap Y = \varnothing$
c	Confidence	c% transaction in *D* that contains *X* also contains *Y*
s	Support	*s%* transaction in *D* that contains $X \cup Y$

A confidence of *c%* for a rule ($X \rightarrow Y$) implies that *c%* of the total transactions having *X* as antecedent also have *Y* as consequent. The confidence can be viewed as the conditional probability that a randomly selected transaction will include all the items in the consequent given that the transaction includes all the items in the antecedent. Equation 1 gives the formula for calculating confidence,

$$conf(X \Rightarrow Y) = \frac{\sup(X \cup Y)}{\sup(X)} \qquad (1)$$

Table 7 lists an abstract set of transaction data used to illustrate association based rule concepts. Six transactions have *item 1* and *item 2* as antecedent, namely, *TID 1*, *TID5, TID 6, TID 7, TID 8,* and *TID 9*. In addition, three transactions have *item 1* and *item 2* as antecedent and *item 4* as consequent, namely, *TID 1*, *TID5,* and *TID 9*. Thus, the confidence of the rule, ***item 1* and *item 2 → item 4***, is 0.3/ 0.6 or fifty percent.

The support of an itemset is the proportion of transactions in the dataset that contain the itemset. The support of a rule can be viewed as the probability that a randomly selected transaction from the database will contain all items in the antecedent and consequent. For instance, in Table 7, support of *item 1* is 80% whereas; support of *item 1* ∪ *item 2* is 60%. For this research, even the rules with support as low as 0.5% are considered. Rules with low support are rare instances but might have interesting applications [66]. Since, dataset analyzed for this research is small, rules with confidence above 50% are considered for analysis.

Table 7: Example of 10 transactions for 5 different items

Transaction ID	item 1	item 2	item 3	item 4	item 5
TID 1	1	1	0	1	0
TID 2	1	0	0	1	1
TID 3	1	0	0	0	1
TID 4	0	1	1	1	1
TID 5	1	1	0	1	0
TID 6	1	1	1	0	1
TID 7	1	1	1	0	0
TID 8	1	1	0	0	1
TID 9	1	1	0	1	0
TID 10	0	1	1	0	1

The lift of the rule *lift* ($X \rightarrow Y$) is the proportion of the support of $X \cup Y$ to support of X and support of Y. Equation 2 gives the formula for calculating the lift.

$$lift(X \Rightarrow Y) = \frac{\sup(X \cup Y)}{\sup(Y) \times \sup(X)} \tag{2}$$

One can interpret the importance of a rule with the value of its lift [67]. The larger the *lift* ratio, the greater is the strength of the rule. In Table 7, lift of rule *item 1* and *item 2* $\rightarrow$ *item 4*, is 0.6/ (0.8 x 0.8) = 0.9375.

From a given dataset, an association based rule algorithm is used to generate rules that have support and confidence greater than a user specified minimum support and minimum confidence. Many algorithms are available for mining association rules from the datasets, for example, Apriori, Eclat, and FP-Growth [68, 69]. The Apriori algorithm is employed to extract association rules for this research. Agrawal explains the details of the Apriori algorithm in [65]. A free data mining software, TANAGRA, is used to extract association rules based on the design differences observed in the product pairs [70]. The application of association rule based algorithm to my research is explained in section 4.1.

4. RESULTS AND DISCUSSION

This section summarizes the results of this research. Section 4.1 summarizes the procedure for analysis of different design features found from existing universal products and the trends observed from the ADA guidelines, the architectural products, and the consumer products. Section 4.2 states the observations and overlap between the rules generated by association ruled based algorithm. Section 4.3 summarizes the existing design guidelines, namely, the seven principles of universal design and the Vanderheiden guidelines. To validate the rules a pilot study, discussed in section 4.3.3, gives a brief overview of the application of the rules to the design of new consumer product.

4.1 Procedure for Data Analysis

The association rule based algorithm and its application to this research is explained in section 3.1.7. The input files to the algorithm for the ADA guidelines, the architectural products, and the consumer products are formulated as explained in section 3.2, 3.3.1, and 3.3.2, respectively. This section analyzes the results of applying the association rule based algorithm to that data. In short, the rule framework is given the user activity and product function (antecedent), what type of change in the product function (consequent) would make it universal?

The items of a transaction are *user activity*, *product function,* and *change*. In this research, the rules having the format *"user activity + product function = change"* are desired. When the designer creates the actionfunction diagram for a product, user-product interaction is known. It would be helpful to know what type of change to a product function, given the user activity, might improve the products accessibility. Rules in other format, such as " *product function* + *change* = *user activity"* or *"user activity* + *change* = *product function"* might be interesting to study. However, for the purpose of analysis, I select the rules having the format *"user activity* + *product function* = *change"*.

The algorithm outputs a set of rules with different combination of the items, namely, user activity, product function and change. Rules are generated based on given minimum values of confidence, support, and lift. The algorithm is not custom designed for this research. Hence, it generated multiple rules with different combination of same set of items. To avoid duplicating of rules, only the rules following the desired format, *"user activity* + *product function* = *change"*, are selected. In addition, the algorithm generates rule with only two items in a transaction. Rule with just two items does not give much insight into the design research, hence they are not considered. The process of sorting of rules is done manually. A custom designed algorithm, to generate rules with all there items of a transaction in the desired format would be beneficial for future research.

After generation of rules by the algorithm, a manual check of the rules ensures that the algorithm overlooks none of the transactions. Note that, the actual design feature is not input to the algorithm. Later, original design features can act as specific examples to help a designer apply these rules. In some cases the user activity changed from typical product to the universal product. However, our main focus remains on the activity in typical product, as these are the ones that make products inaccessible. Further sub-sections explain the specific outputs of the ADA guidelines, the architectural products, and the consumer products.

4.1.1 Trends Observed in the ADA Guidelines

This section discusses the results of ADA guidelines. Table 8 and Table 9 lists the rules generated by the Apiori algorithm. The algorithm is programmed to select association rules having values of confidence, support, and lift above a set value. Altogether, 129 rules are generated whose confidence, support, and lift are above 40 %, 0.5 %, and 1 respectively. The value of minimum confidence, support, and lift are chosen such that maximum number of rules with all the transaction sets is generated. As mentioned earlier, rules with low support are rare instances but might have interesting applications.

On comparison of the algorithm's results with manual results it is observed that the algorithm generates less number of rules in the desired format i.e., *"user activity + product function = change"*. Most of the rules either have only two items of the transaction or have either *user activity* and/ or *product function* as consequent. Hence, for ADA guidelines the rules with format "*product function + change = user activity"* are also considered. For example, either a parametric, morphological, or functional change to product function *indicate status* can make the activity of *hearing/seeing functions* more inclusive. Hence the format *"Hearing/ Seeing functions + Indicate Status =change"* would not make sense.

The format, "*product function + change = user activity',* can be interpreted as what user activity will be simplified on changing the product function in a specific way.

The difference in the format is due to the fact that particular combination of user activity and product function had more than one type of change associated with it. This observation was very specific to the ADA guidelines. The large number input transactions, 142, might be a possible explanation. In a large dataset variety of examples are included which might show more than one type of change for the same user activity – product function pair. Table 8 tabulates the rules with the format *"user activity + product function = change"*. While, Table 9 shows the rules in the format *" product function + change = user activity"*.

Table 8. Results from association rule based algorithm for the ADA guidelines with user activity and product function as antecedent and change as the consequent

ADA Guidelines			Number of rules: 15			
	Antecedent		Consequent	Measures		
	User Activity	Product function	Change	Confidence (%)	Support (%)	Lift
1	n/a	Guide Solid	Functional	66.7	1.4	4.77
2	Communicating - receiving	Indicate Status	Functional	60	2.1	4.29
3	Communicating - receiving	Sense/ Indicate Status	Functional	100	0.7	7.15
4	Grasping	Secure Hand	Functional	50	2.1	3.58
5	Grasping	Secure Human	Functional	100	0.7	7.15
6	Moving around	Secure Human	Functional	50	1.4	3.58
7	n/a	Position solid	Functional	100	0.7	7.15
8	Manipulating	Guide Solid	Morphological	85.7	8.4	8.17
9	Pulling/ Pushing	Guide Solid	Parametric	100	0.7	1.32
10	n/a	Import / Export Human	Parametric	100	1.4	1.32
11	Communicating - receiving	Indicate Status	Parametric	100	2.1	1.32
12	Caring for body parts	Position Human	Parametric	100	1.4	1.32
13	Maintaining a body position	Position Human	Parametric	88.9	11.2	1.32
14	Moving around	Import / Export Human	Parametric	100	33.6	1.32
15	Reaching	Position Hand	Parametric	100	11.9	1.32

Table 9. Results from association rule based algorithm for the ADA guidelines with product function and change as antecedent and user activity as the consequent

ADA Guidelines			Number of rules: 8			
	Antecedent		Consequent	Measures		
	Product function	Change	User Activity	Confidence (%)	Support (%)	Lift
1	Indicate Status	Functional	Hearing/ Seeing functions	100	3.5	6.87
2	Guide Liquid	Morphological	Washing whole body	100	1.4	35.75
3	Indicate Status	Morphological	Hearing/ Seeing functions	100	0.7	11.00
4	Indicate Status	Parametric	Hearing/ Seeing functions	58.3	4.9	6.42
5	Guide Solid	Parametric	Manipulating	50	1.4	5.10
6	Guide Liquid	Parametric	Washing whole body	100	1.4	35.73
7	Secure Hand	Parametric	Grasping	100	2.1	20.43
8	Secure Human	Parametric	Moving around	100	1.4	2.75

The rules having high values of confidence and support that make a strong case for application to the design of universal products, are listed below:

Moving around + Import / Export Human =Parametric
Reaching + Position Hand =Parametric
Maintaining a body position + Position Human =Parametric
Manipulating + Guide Solid =Morphological
Indicate Status + Parametric = Hearing/ Seeing functions

4.1.2 Trends Observed in the Architectural Products

This section discusses the association rules obtained by the Apriori algorithm for the consumer product pairs. Out of a total of 84 association rules generated, 8 rules having all three items and the desired format, *"user activity + product function = change"* are selected. For the architectural products, all of the association rules selected are in the desired format. Almost all the rules have 100 % confidence.

Table 10. Results from the association rule based algorithm for the architectural product pairs

Architectural Products			Number of rules: 8			
	Antecedent		Consequent	Measures		
	User Activity	Product function	Change	Confidence (%)	Support (%)	Lift
1	Manipulating	Actuate Signal	Morphological	50	3.6	3.5
2	Grasping and Manipulating	Guide Solid	Morphological	100	7.1	7
3	Transferring oneself	Import / Export Human	Morphological	100	3.6	7
4	Moving around	Import / Export Human	Parametric	100	10.7	1.17
5	Reaching	Position Hand	Parametric	100	32.1	1.17
6	Carrying in hands	Position Solid	Parametric	100	10.7	1.17
7	Maintaining a body position	Position Human	Parametric	100	25	1.17
8	Seeing	Indicate Status	Parametric	100	3.6	1.17

In the case of the function *actuate signal* and *manipulating* activity; the change is either parametric or morphological. Hence, the confidence of this rule is 50%. There is one transaction of each case in the input data set. However, the algorithm gives the rule only in the format *Manipulating + Actuate Signal= Morphological* and not in the format *Manipulating + Actuate Signal = Parametric*. A manual check of the rules generated by the algorithm helps to track such flaws. Note that, the algorithm is implemented for quicker analysis of the input parameters. The algorithm helps to perform numerous iterations with different combinations. However, my main goal is to find rules, not necessarily association rules, for the purpose of enhancing universal design guidelines.

Some of the rule having high values of confidence and lift are listed below:

Maintaining a body position + *Position Human* = *Parametric*
Reaching + *Position Hand* = *Parametric*
Carrying in hands + *Position Solid* = *Parametric*
Moving around + *Import / Export Human* = *Parametric*
Grasping and Manipulating + *Guide Solid* = *Morphological*

4.1.3 Trends Observed in the Consumer Products

Out of the algorithm generated 126 association rules for the consumer products, 16 rules follow the format *"user activity + product function = change"*. Table 11 lists the rules for consumer products with values of confidence, support, and lift above 40 %, 5 %, and 1 respectively. As explained for the ADA guidelines, the value of minimum confidence, support, and lift are chosen such that maximum number of rules with all the transaction sets is generated.

Table 11. Results from the association rule based algorithm for the consumer product pairs

Consumer Products			Number of rules: 16			
	Antecedent		Consequent	Measures		
	User Activity	Product function	Change	Confidence (%)	Support (%)	Lift
1	Sitting	Guide Human	Functional	100	10.3	2.9
2	Transferring oneself	Guide Human	Functional	100	3.4	2.9
3	Manipulating	Guide Solid	Functional	50	10.3	1.45
4	Pushing/ Pulling	Guide Solid	Functional	100	3.4	2.9
5	Maintaining a body position	Position Human	Functional	100	6.9	2.9
6	Grasping and Twisting	Guide Solid	Functional	100	3.4	2.9
7	Grasping	Guide Solid	Morphological	100	3.4	2.9
8	Manipulating	Guide Solid	Morphological	50	10.3	1.45
9	Pulling	Guide Solid	Morphological	100	3.4	2.9
10	Pushing- lower extremity	Guide Solid	Morphological	100	3.4	2.9
11	Communicating - receiving	Indicate Status	Morphological	100	3.4	2.9
12	Manipulating	Actuate Signal	Morphological	100	3.4	2.9
13	Transferring oneself	Import / Export Human	Morphological	50	3.4	1.45
14	Grasping	Secure Hand	Parametric	100	20.7	3.222
15	Manipulating	Secure Hand	Parametric	100	6.9	3.222
16	Transferring oneself	Import / Export Human	Parametric	50	3.4	1.61

The rules having the highest support and highest confidence are listed below.

Grasping	*+ Secure Hand*	*= Parametric*
Sitting	*+ Guide Human*	*= Functional*
Manipulating	*+ Guide Solid*	*= Functional*
Manipulating	*+ Guide Solid*	*= Morphological*

Note that application of the rules generated is explained as applied to 15 products discussed in section 4.4

4.2 Observations

Overlap between the rules generated by the algorithm for the ADA guidelines, architectural products, and consumer products is depicted in Figure 14. Abbreviations used for the representation are listed in Table 12. Figure 14 shows that no rules overlap between the ADA guidelines and the consumer products. No overlap suggests that ADA guidelines are not directly applicable to the consumer products.

However, there is considerable overlap of rules between architectural products and the ADA guidelines. Note that the rules common to ADA guidelines and architectural products are also the ones having high values of confidence and support. The ADA guidelines and architectural product have similar user - product interface. The size and space relation between the user and the product is similar for the ADA guidelines and architectural products. Thus, ADA guidelines can be adapted for the design of universal architectural products.

In the case of overlap between architectural products and consumer products, overlapping rules have values of support around 3.6 %. Low support indicates that such instances are rare. Similar user-product interface may not necessarily occur in the new product design. The consumer products are diverse and included wide range of user activities involved while using the product. In contrast the architectural products are mostly concerned with gross user access. The scope of product functions for the consumer products is wide- ranging. Discrepancy in the result can be largely attributed to the range of user activities and product functions in consumer domain as opposed to the architectural domain. Therefore, translation of rules from the architectural domain to the consumer domain is not obvious.

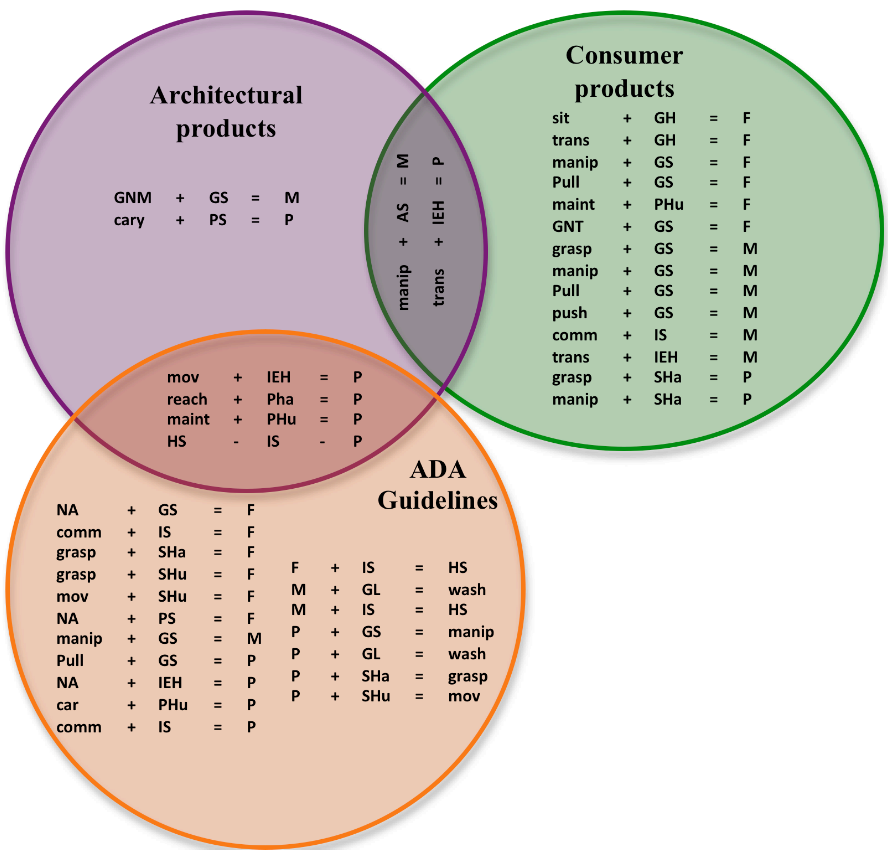


Figure 14. Venn diagram representing the overlap between rules based on the ADA, the architectural product pairs, and the consumer product pairs

Table 12. Abbreviations used in Figure 14

Abbrev.	User Activity	Abbrev.	Product Function
NA	Not applicable	IS	Indicate Status
comm	Communication	IEH	Import / Export Human
HS	Hearing/ seeing	SHa	Secure Hand
grasp	Grasping	SHu	Secure Human
mov	Moving around	GL	Guide Liquid
wash	Washing whole body	GS	Guide Solid
manip	Manipulating	GH	Guide Human
Pull	Pulling/Pushing	PS	Position solid
car	Caring for body parts	PHu	Position Human
maint	Maintaining body position	Pha	Position Hand
reach	Reaching	AS	Actuate Signal
GNM	Grasping and Manipulating		
trans	Transferring Oneself		
cary	Carrying in hands	**Abbrev.**	**Change**
sit	Sitting	F	Functional
GNT	Grasping and turning	M	Morphological
push	Pushing	P	Parametric

To sum up, rules from the ADA guidelines can be applied to specific products in the architectural product category but not in general to any device. The scope of the architectural domain needs to be clearly stated before application of any rules. Size and space relation between the user and a product is the main characteristic of the architectural products.

4.3 Comparison with Existing Methods of Universal Design

Once a set of rules is determined, the next step is to validate these rules. Rules stated in sections 4.1.1, 4.1.2, and 4.1.3 are compared with the existing guidelines. The following sections give a brief overview of the existing guidelines and present a pilot study to explore some initial validation of the rules.

In this research, I am trying to formulate rules that can be easily implemented. A long-term goal is to have a set of rules, which can be fed into a computer code. The code would then identify the functional blocks that have scope for improving accessibility and indicate the type of change that would be helpful. In such a scenario, a product designer need not have great insight into various forms of disability and user limitations.

4.3.1 Seven Principles of Universal Design (NCSU)

Owing to the growing awareness for universal design of products and environments, researchers have consistently strived to improve the design methodology for developing universal products. A team of researchers organized through The Center for Universal Design at North Carolina State University has compiled seven principles of universal design [7]. These principles have been well received by designers in a range of disciplines.

The seven principles are: 1. Equitable use, 2. Flexibility in use, 3. Simple and intuitive use, 4. Perceptible information, 5. Tolerance for error, 6. Low physical effort, and 7. Size and space for approach and use. For each principle, several guidelines have been listed. The following sections explain the application of each of these principles.

Principle 1- *equitable use* states that the design should be useful and marketable to people with diverse disabilities. As an example, power doors with sensors are convenient for all shoppers. For equal provision of privacy, security, and safety to all users, ATM screens that tilts are helpful.

Principle 2 - *flexibility in use* states that the design should accommodate a wide range of individual preferences. Consider a built-in tub seat with multiple grab bars; the user can use the shower in either a seated or standing position, thus providing a choice in the method of use. Another example is Fiskars large-grip scissors that accommodate both right-handed and left-handed users.

Principle 3 - *simple and intuitive* use of the design eliminates unnecessary complexity and is easy to understand. To be consistent with a user's intuition and expectation, automobile power-seat control mimics the shape of seat, as shown in Figure 15. Other specific guidelines are to accommodate a wide range of language skills, arrange information consistent with importance, and provide feedback after task completion.

Figure 15. Automobile power-seat controls in the shape of a seat provide simple and intuitive use [41]

Principle 4 - *perceptible information* explains the necessity of the design to communicate effectively with a user. Specific guidelines are tactile information in the form of raised characters or Braille, contrasting colors for better visibility, textured contrast on maps, color coding, and captioning on television.

Principle 5 - *Tolerance for error* states that the design should minimize hazards due to unintentional action. Tolerance for error can be achieved in many ways. For example, provision of features such as an ‘UNDO’ option on the computers, prominent labeling to warn for hazards, additional shielding for slicer blades, and ridge guard around a start button, can discourage unconscious actions.

Principle 6 - *Low physical effort* emphasizes that the design should be comfortable to use with minimum fatigue. This can be achieved by allowing a user to maintain a neutral position, use reasonable operating forces, minimize repetitive actions, and minimize sustained physical efforts. Examples of products that achieve low user physical effort include ergonomic keyboards, electric power to eliminate opening effort of a door, ¼ turn caps for medicine bottles, and free rolling caster wheels on travel bags.

Principle 7 - *Size and space for approach and use* explains the importance of product access. Detailed guidelines are provide clear line of sight, make the reach to all components comfortable for either a seated or standing user, accommodate variation in hand and grip size, and provide adequate space for assistive devices. Principle 7 covers a broad scope of ADA guidelines without providing the specific details of the ADA.

Though the seven principles of universal design provide high-level guidance, they provide more of an evaluation aid than a design or synthesis aid for product design. This can be seen by a closer examination of the principle 6 - products need to be designed for low physical effort by minimizing repetitive actions. Though some example products are provided above, the general question remains; exactly how can one design a product to minimize repetitive actions and thus require low physical effort. The Seven principles tend to describe an outcome objective of the design rather than specific design guidance that can be used during conceptual and embodiment design.

4.3.2 Vanderheiden Guidelines

Researchers in the Trace R&D Center at University of Wisconsin-Madison created a set of guidelines for the design of consumer products [10]. These guidelines will be referred to as the Vanderheiden guidelines. The Vanderheiden guidelines advocate the design of consumer products to increase the product's accessibility for individuals with disabilities or those who are aging. For defining the scope of the guidelines, consumer products are defined as '*appliances and other electronic and mechanical devices available to the mass market for use in the home, school, office, or for use by the general public in the community.*' The Vanderheiden guidelines are created by combined efforts of industry, consumers, researchers, and government.

The Vanderheiden guidelines are organized into multiple parts. Part 1 introduces the guidelines themselves. Part 2 describes the disabilities and the functional limitations faced by a user due to the disability. For example, vision impairment reduces the functioning capability that requires eye-hand coordination. The primary focus of the Vanderheiden guidelines is on disabilities related to seeing, hearing, reaching, and manipulating. As a contrast, the implementation of ICF as developed in this research eliminations the intermediate step of identifying each disability and it's resulting physical impairments.

In part 3, guidelines for accessible design of consumer products are grouped into four sections. Section 1 and 2 deal with 'outputs and displays' and 'inputs and controls' respectively. Each section has several sub-sections with detailed examples and additional information. Typical examples are the size of a microphone or a headphone jack on a device, the addition of a tactile volume control, and a visual indicator of loudness for noisy surroundings. In the case of the input-output devices, Vanderheiden guidelines provide more specific detail than ADA guidelines. In this context, they are more applicable to input-output type consumer products.

Part 3, section 3 of the Vanderheiden guidelines, *Manipulations* of *the Accessible Design of Consumer Products* is closely related to the goals of the research presented here. The first three sub-sections of section 3 are of particular interest, namely, insert or remove, handle or open, remove or replace objects. The last sub-section covers the ‘understand’ feature that deals with the memory of aging individual. However, the scope of this research is limited to the physical impairments and excludes discussion on any cognitive disabilities like Alzheimer’s disease or autism.

Part 3, section 4 explains guidelines for the documentation of accessible operating instructions. Some of these guidelines also provide designer guidance for safety features to be considered while designing a product. Documentation and safety features in not included in my research.

In general, Vanderheiden guidelines tend to be focused on products in electronic communication or information technology. Some of these guidelines are useful primarily for evaluation, while others include suggestions that augment product synthesis.

Vanderheiden guidelines suggest maximizing the number of people who can see or hear. Nevertheless, basic design questions remain, such as how to actually measure such parameters, and how to ensure that the design considers right sample set of users? More specific guidelines like volume of the announcement should be above 50 dB would provide better guidance. As a contrast, such design details are mentioned explicitly in the ADA. Using the Vanderheiden guidelines, designers get acquainted with the disabilities about which they have limited knowledge. For instance, problems such as epilepsy are not exclusively addressed in the ADA.

To apply the Vanderheiden guidelines successfully, a designer must read in sufficient detail to create both familiarity and understanding. In practice, the interpretation of a guideline might vary among designers. The application of the guidelines is not straightforward, especially, for the products not explained in the examples. In general, the Vanderheiden guidelines are not clearly applicable to the design of mechanical devices in the consumer product category.

4.3.3 Pilot Study for Validation

A pilot study is conducted to validate the set of rules obtained in section 4.1.2. The main purpose of this exercise is to compare the improvement in the design of a product that results from applying guidelines and rules for universal design. The existing guidelines from Vanderheiden and NCSU are used as a benchmark for comparison.

In the study, participants are asked to design a universal clothes washer. The participants for the pilot study are three mechanical engineering students; two graduate level students and one undergraduate level student. The participants being a part of design research group are familiar with the concepts like activity diagram and functional modeling. I recorded the verbal response of participants regarding design ideas, till they ran out of ideas. Each participant is asked to work individually for a total duration of around 30 to 45 minutes. No sketching was done during the pilot study hence; sketches are not included in the discussion here.

Figure 16 shows a typical washer designs in both a front-loading (left) and top-loading (right) configuration. These examples are given to the participants. Providing both front and top-loading examples are used to suggest that the washer drum need not always rotate on a vertical axis.

Figure 16. The existing design of a typical washer, front-loading washer (left) [71] and top-loading washer (right) [72]

In the first phase of the experiment, all the participants are provided with the Vanderheiden guidelines and the NCSU seven principles of universal design. Specific guidelines relevant to the design problem are highlighted. For example, from the Vanderheiden guidelines, *'Facilitating orientation and insertion* by *Ensuring that objects can be inserted (and removed) with minimal user reach and dexterity'* and '*Facilitating removal* by *Using push-button ejection, or automatic (motorized) ejection mechanism'* are highlighted. Out of the seven principles, Principle One: Equitable Use stating that *the design is useful and marketable to people with diverse abilities* is most relevant. The four detailed guidelines of *principle one* are:

- *Provide the same means of use for all users: identical whenever possible; equivalent when not,*
- *Avoid segregating or stigmatizing any users,*
- *Provisions for privacy, security, and safety should be equally available to all users, and*
- *Make the design appealing to all users.*

Given the problem and the guidelines, the participant's verbal response for designing a universal clothes washer is written down. Participant suggestions included providing a funnel to direct clothes into the washer, some other provision to shove clothes into the washer with gross hand and arm use, a larger opening of the washer door, a push button system to open the washer door, use of gravity to load or unload clothes, an external cart to carry clothes into the washer, a mechanism to eject clothes out of washer, allow the orientation of washer drum to articulate for easy loading and unloading, and movable washer controls (connected to washer by wire or wireless) such that it can be positioned according to the user's convenience.

Some of the ideas generated by the participants involved complicated functional changes to original design of washer. Vanderheiden guidelines are good for small parts like a disk or a floppy drive, where ejection or articulation mechanism would be comparatively simpler. Imagine a mechanism to articulate a 250-lbf washer and the associated cost and complexity. Obviously, translation of the guidelines from electronic products to mechanical devices does not seem to be proportional. The existing guidelines are detailed and well compiled. However, while implementing these guidelines the designers tends to think about all the parts simultaneously and jumps from one idea to the other.

In the second phase of experiment, the participants are provided with actionfunction diagram of a washer and a set of rules generated in this research. A washer for clothes falls within the notion of an architectural product domain, hence, the set of rules based on architectural products is considered. Rules provided to the participants are reproduced in Table 13. Figure 17 shows the actionfunction diagram of a typical washer.

Table 13. Rules provided for universal design of washer

	Antecedent		Consequent
	User Activity	**Product function**	**Change**
1	Manipulating	Actuate Signal	Morphological
2	Grasping and Manipulating	Guide Solid	Morphological
3	Transferring oneself	Import / Export Human	Morphological
4	Moving around	Import / Export Human	Parametric
5	Reaching	Position Hand	Parametric
6	Carrying in hands	Position Solid	Parametric
7	Maintaining a body position	Position Human	Parametric
8	Seeing	Indicate Status	Parametric

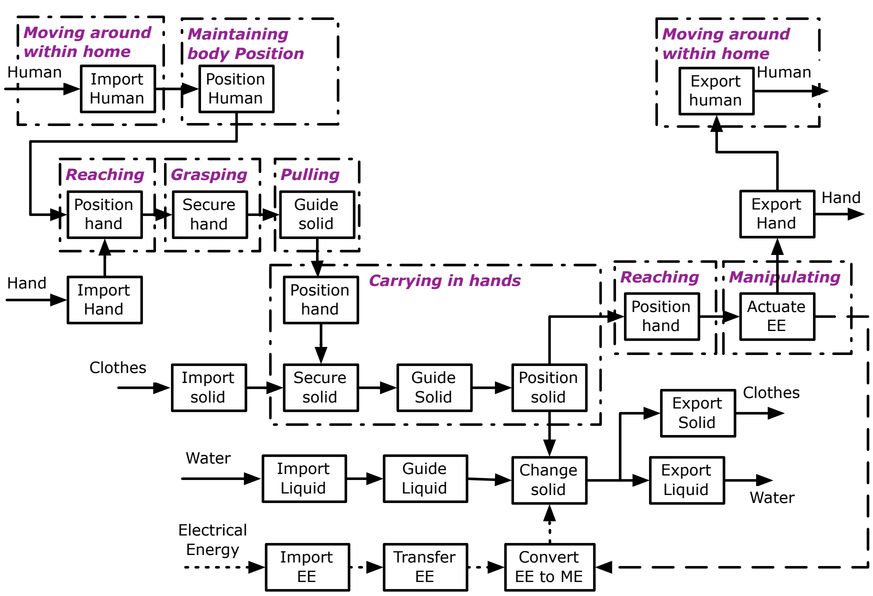
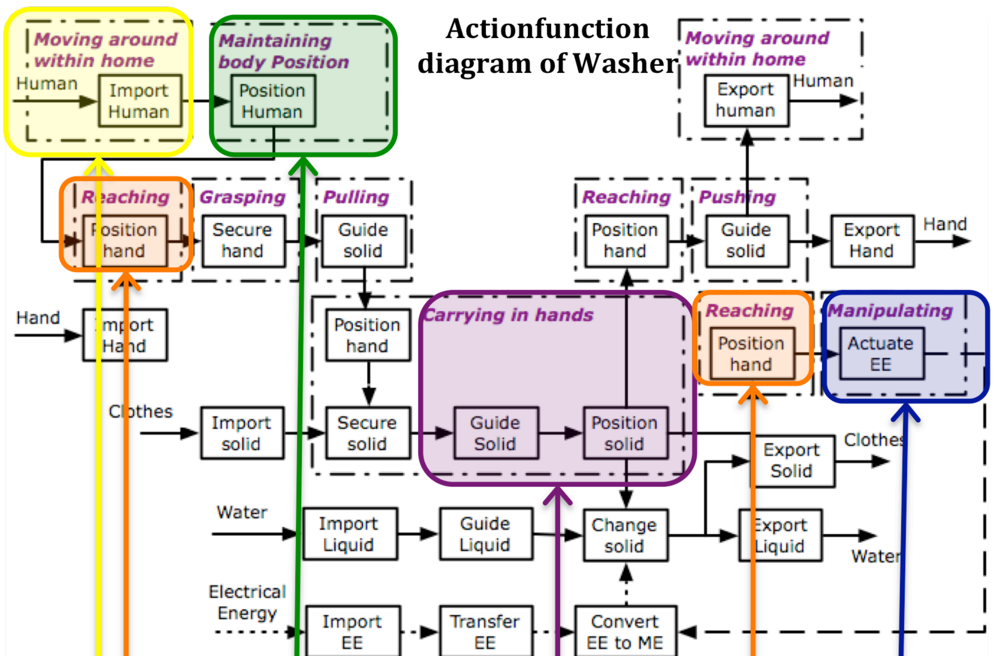


Figure 17. Action function diagram of a typical washer

In the exercise, the concept of the actionfunction diagram, ICF codes for the user activities, and the product function in functional basis are explained to all participants for efficient application of the rules. Specifically, three types of changes, namely, parametric, morphological, and functional, are explained along with examples from the architectural domain to help the participants visualize any implementable change. One result to note is that though the ICF lexicon maintains uniformity, its meaning is not obvious to the participants. Detailed explanation and example of each activity occurring in actionfunction diagram is helpful. Participants looks through a '*user activity – product function'* pair in the actionfunction diagram and then find the type of change based on the rules that makes that user activity more inclusive.

Figure 18 shows example of implementation of the rules developed in this study with help of actionfunction diagram of a clothes washer. Note that is is only for illustration purpose and not provided by the participants. Each color highlights the rule for design of architectural products and the corresponding '*user activity – product function'* pair in the actionfunction diagram. For instance, a morphological change to '*user activity – product function'* pair given by *manipulating* and *actuate signal* makes the washer more accessible. The activity of operating the washer controls is represented as *manipulating*, which sends appropriate signals to the washer. A morphological change in this case would mean replacing round control knobs by touch buttons. Also note that the '*user activity – product function'* pair of *reaching* and *position hand* is repeated twice. One suggests location of door and the other suggests location of washer controls. Both objects to be reached must be parametrically located within users reach range.

All participants noticed that the actionfunction diagram provided a structured way to approach the problem. For instance, participants could focus on a single function at a time such as the door of a washer, washer controls, washer's location, etc. Another interesting outcome is that a participant did not have to list various forms of disabilities. Usually, making an activity simpler or eliminating it altogether solves the problem.



	Antecedent		Consequent
	User Activity	Product function	Change
1	Manipulating	Actuate Signal	Morphological
	Grasping and Manipulating	Guide Solid	Morphological
	Transferring oneself	Import / Export Human	Morphological
4	Moving around	Import / Export Human	Parametric
5	Reaching	Position Hand	Parametric
6	Carrying in hands	Position Solid	Parametric
7	Maintaining a body position	Position Human	Parametric
	Seeing	Indicate Status	Parametric

Rules for Design of Architectural Products

Figure 18. Illustration of implementation of the rules provided in Table 13 on an actionfunction diagram of a washer

A universal washer design from *Panasonic, Inc.* is shown in Figure 19 [73]. In this design, a simple parametric change greatly improves the accessibility. The universal design guidelines and associated methods used in the pilot study exercise did not lead to an equivalent solution as that produced by Panasonic. In general, the ideas generated by participants were more complicated than the simple parametric change found in the Panasonic washer. The most similar solution obtained in the pilot study was a raised, front-loading washer. The raised front-loading solution puts the door at a height convenient for most users. The fact that a raised washer's installation requires a sturdy platform at an ergonomic height makes this solution more complicated than the tilted drum washer.

Figure 19. A simple parametric change in tilted drum washer- dryer makes it easier to load and unload laundry [73]

4.4 Product Pairs for Validation

This section discusses the application of rules generated in section 4.1 for the design of new universal products. Figure 20 shows that a simple parametric change in the bottle cap makes it more accessible for individuals with reduced hand functioning. The activity of *grasping* is made easier due to change in the shape of a cap. The user-product interaction is illustrated in the actionfunction diagram shown in Figure 21.

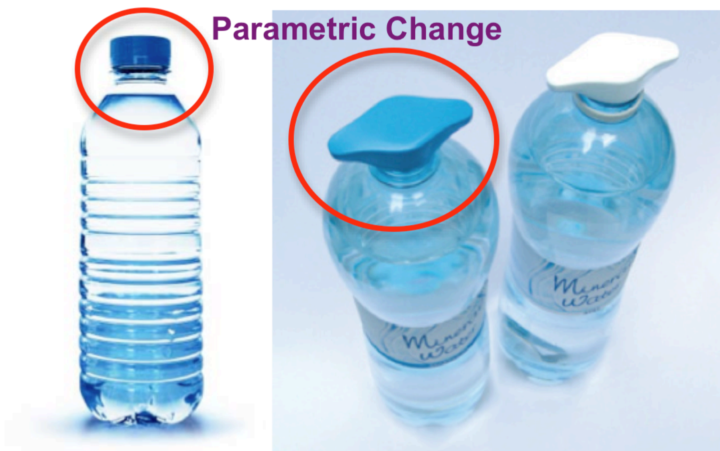


Figure 20. A parametric difference in the typical bottle cap (left) [74] makes the user activity of *grasping* easier in the universal bottle cap (right) [75]

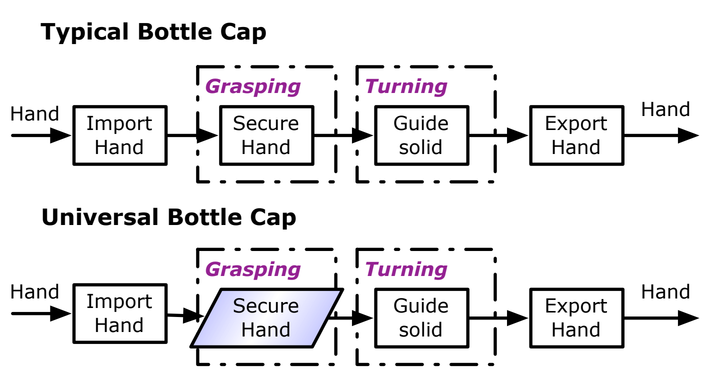


Figure 21. Actionfunction diagram for bottle cap illustrating the parametric difference in the typical (top) and universal (bottom) product

For improving accessibility, rule #14 in Table 11 suggest a parametric change for user- product interaction of activity *grasping* and function *secure hand*. Similarly, rule #7 in Table 9, suggests that the activity of *grasping* is improved when a parametric change is made to the product function, *secure hand*.

Figure 22 shows a typical electrical plug (left) and a universal electrical plug (right). The user activity of removing and inserting plug is modeled as *grasping*. An indentation on the typical plug and a handle on universal plug provide the function of *secure hand*. Figure 23 shows the actionfunction diagram for the typical and universal electric plug. The user - product interaction is similar to that of the bottle cap and can be similarly analyzed. Thus for the bottle cap and the electrical plug a simple parametric change in the geometry makes it more inclusive.

Figure 22. Typical electrical plug (left) can be cumbersome to remove; however, a parametric change to the plug geometry makes removal easier as shown on right [41]

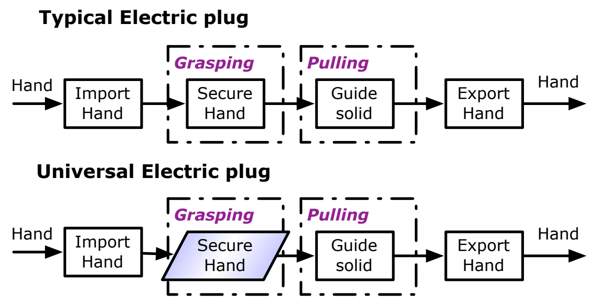


Figure 23. Actionfunction diagram for electrical plug illustrating the parametric difference in the typical (top) and universal (bottom) product

Figure 24 shows a typical wristwatch (left) and a Close Enough Watch (right). Large easy-to-read numbers of the Close Enough Watch is better for individuals with vision impairment. The number indicates the hour while the fractions of hour are represented by shaded figures. Thus, at a glance the Close Enough Watch tells the rounded off time. Figure 25 illustrates the morphological difference in the actionfunction diagram of a Close Enough Watch in comparison with a typical wristwatch. A morphological change to the product function *indicate status* makes the activity *seeing* easier.

Rule #1, rule #3 and rule #4 in Table 9, states that either a functional, morphological, or parametric change to the function - *indicate status* makes the product more accessible for the activity of *seeing functions*. A parametric change to a wristwatch suggests larger numbers and contrast color combination of the hands and dial. A functional change to wristwatch for improving accessibility might be additional voice output to indicate time. The Close Enough Watch is an excellent example of innovative design demonstrated by a morphological change.

Figure 24. The Close Enough Watch [76] (right) makes time telling easier for the vision-impaired with its large easy-to-read numbers. This is example of a morphological change to typical wristwatch [77] (left)

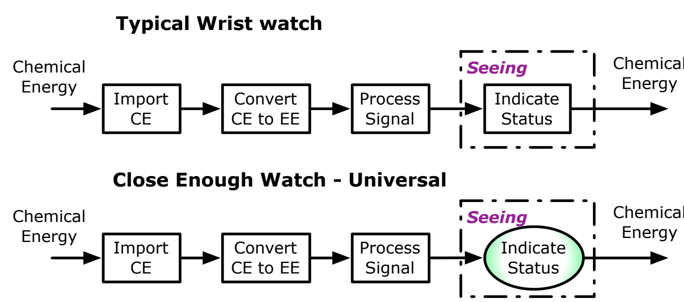


Figure 25. Actionfunction diagram of a typical wristwatch (top) and a Close Enough Watch (bottom)

Figure 26 shows a typical trash-can (on the left) and a universal designed trash-can (right) as used in Toronto. Figure 27 shows actionfunction diagrams for typical and universal trash can. As explained for the Close Enough Clock, rule #1, rule #3 and rule #4 in Table 9, states that either a functional, morphological, or parametric change to the function - *indicate status* makes the product more accessible for the activity of *seeing functions*. Addition of redundant signage with both symbols and text in universal trashcan serves as a functional change to the product for easy identification by maximum number of users.

Figure 26. Trash cans in Toronto [78] (right) have redundant signage with both symbols and text. The flaps of universal trash can opens either by a foot pedal or by direct pushing, thus, demonstrating a morphological change in comparison with the normal flap of a typical trash can (left) [79]

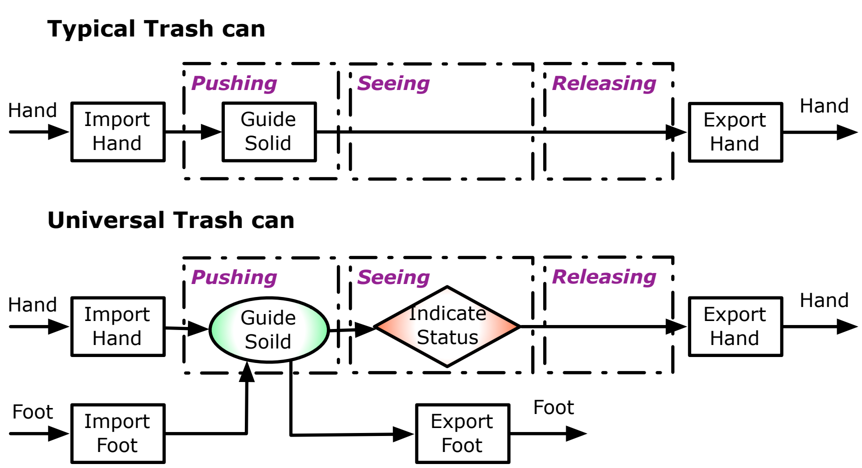


Figure 27. Actionfunction diagram of a typical (top) and universal (bottom) trash cans illustrating a morphological and functional change for improving the accessibility

Flaps of the universal trashcan can be opened either by pushing directly with hands or by a foot pedal. Rule #10 in Table 11 suggests a change in morphology of a lever mechanism to enable the user to *push* either with the upper or the lower extremity for *guiding solid*. Provision of foot pedal acts as morphological change against the normal flaps that needs to be pushed by hand.

Figure 28 shows a typical thermometer (left) and a universal digital thermometer, i-Temp by Omoron (right). The universal features of i-Temp are large digital display, flat tip sensor, and on/off button at top of device. The large digital display makes the activity of *seeing functions* better accessible. In the typical thermometer, the temperature is indicated by level of mercury, which is difficult to read. Again, as suggested by Table 9, either type of change can improve accessibility of the user-product interaction of *seeing functions* and *indicate status*. Similar to the Close Enough Watch, the display of i-Temp thermometer is an example of morphological change.

Figure 28. The i-Temp thermometer by Omoron [80] (right) has an extra large display to make reading easier. The flat tip sensor will enable the patient to secure the thermometer easily. Typical thermometer is shown on left [81]

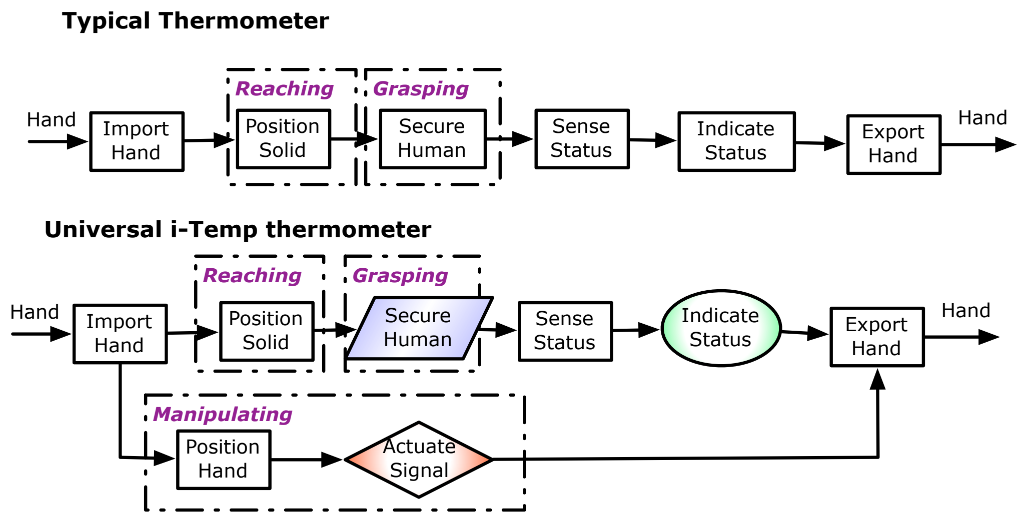


Figure 29. Actionfunction diagram of a typical thermometer (top) and universal thermometer (bottom)

A flat tip sensor in the i-Temp thermometer enables better securing of the thermometer as opposed to round bulb in the typical design. A parametric change to the tip of the sensor ensures better grip of the thermometer. As suggested by rule #7 in Table 9, a parametric change to function *secure* is better for *grasping* activity. Similarly, rule #14 in Table 11 supports the parametric change to function of *securing*. Note that, the user activity for placing the thermometer is approximated to *grasping*.

The on/off button is an additional feature in the digital thermometer, which is a functional change to *actuate signal*. The start/ stop activity is modeled as *manipulating*. Rule #1 in Table 10 and rule #12 in Table 11 recommend a morphological change to the actuating mechanism in typical device. However, in the mercury type thermometer on/off button is not required. To make a morphological change, there must be a similar function in the typical version of the product.

Figure 30 shows an upper arm blood pressure monitor with an automatic cuff wrapping and supporting armrest for correct location of arm on right. A typical blood pressure monitor is shown on the left in Figure 30. Figure 31 illustrates the difference between typical and universal blood pressure monitor with an actionfunction diagram.

Figure 30. Upper arm blood pressure monitor [82] (right) with automatic cuff wrapping and supporting armrest for correct location of arm. A typical blood pressure monitor shown on left [83]

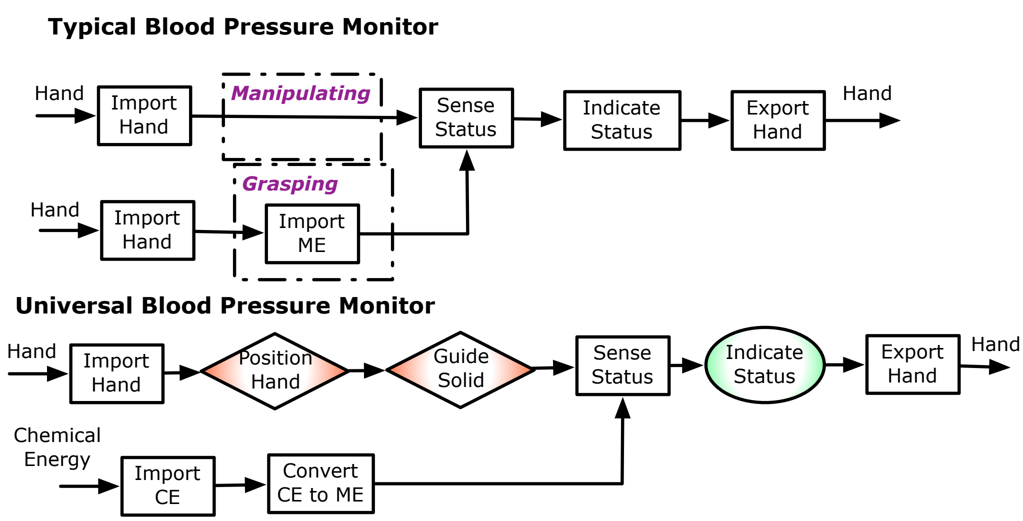


Figure 31. Actionfunction diagram of a typical blood pressure monitor (top) and universal blood pressure monitor (bottom)

In the universal design of blood pressure monitor, the automatic cuff-wrapping feature adds function of *guiding solid*, thus eliminating the *manipulating* activity. This is accordance with rule #3 in Table 11 that suggests a functional change to function *guide solid* and activity *manipulating*. The additional function of *positioning hand* is provided by the armrest. The positioning feature is supported by rule #7 in Table 8 that recommends a functional change for the *positioning* function. In line with the T-temp and Close Enough Watch, the display of universal blood pressure monitor is an example of morphological change to function *indicate status*.

Figure 32 shows a typical syringe (left) and a universal design of an OXO syringe. Figure 33 shows the actionfunction diagram for typical and universal syringe. The OXO syringe is designed for patient's use with design features that include pre-loaded medication, an easy to grip and easy-to-push thumb pad, an added loop for easy removal of the needle cover, and an easier to read magnified barrel.

The easy to push thumb pad and easy to grip feature helps the activity of *grasping*. Rule # 14 of Table 11 suggests a parametric change to the function *secure hand* to ease the activity of *grasping*. Rule # 14 of Table 11 also applies to the added loop for easy removal of the needle cover.

Similarly, the magnified barrel is an example of a parametric change to *indicate status* function, which improves the activity of *seeing functions*. The parametric change of magnified barrel readings is supported by rule # 4 in Table 9. OXO syringe is perfect example of simple parametric changes that greatly improves accessibility.

Figure 32. OXO syringe (right) have features like; pre-loaded medication, easy to grip, easy removal of needle cover, easy-to-push thumb pad, easier to read magnified barrel [84]. Typical syringe is shown in left for comparison [85]

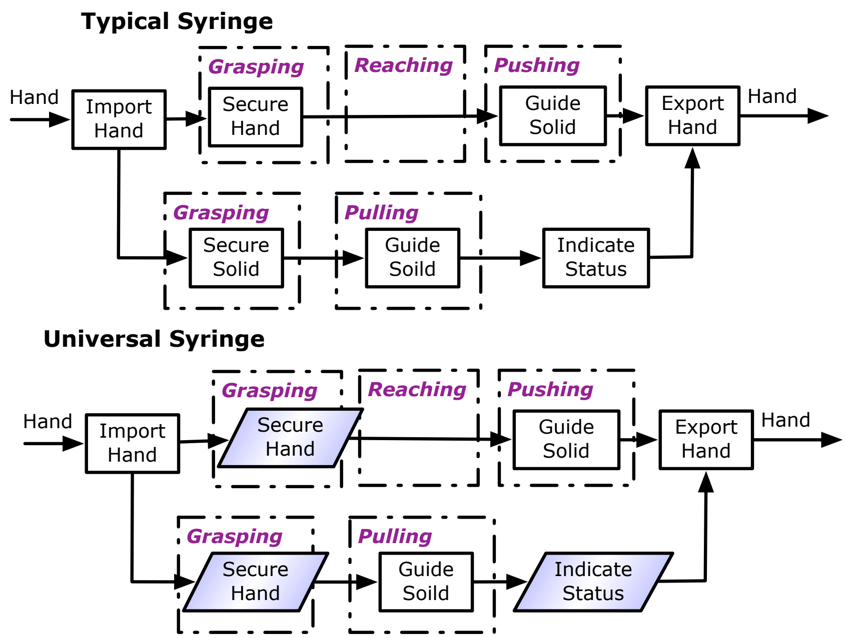


Figure 33. Actionfunction diagram of a typical syringe (top) and universal syringe by OXO (bottom)

Figure 34 shows a regular seat belt (left) and a seat belt adaptor (right). The seat belt adaptor is an add-on component to the regular seat belt such that it facilitates grip, location and insertion of the tongue in the slot, and release of the locking mechanism.

The actionfunction diagram of the typical seatbelt and seatbelt with the adaptor is shown in Figure 35.

Figure 34. The seat belt adaptor system [86] (right) is added to the buckle. The seat belt adaptor facilitates griping, positioning, and insertion of the buckle tongue into the slot as well as releasing of the locking mechanism. Typical seat belt is shown on left [87]

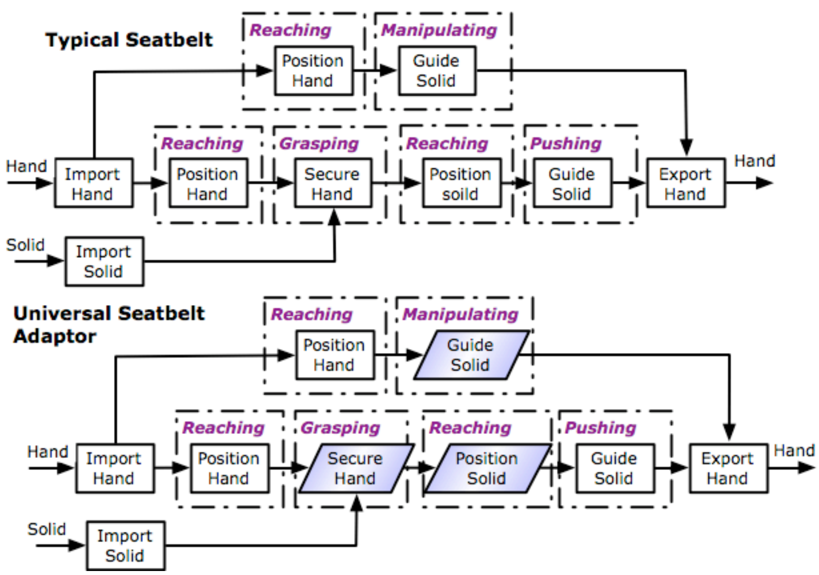


Figure 35. Actionfunction diagram of a typical seatbelt (top) and universal seatbelt with adaptor (bottom)

The added grip provided by the adaptor parametrically improves *secure hand* function, thus facilitating the grip that is represented by *grasping* activity. The user activity product function pair of *grasping* and *secure hand* is suggested to change functionally by rule #4 of Table 8. Whereas, the user activity – product function same pair is expected to change parametrically as given by rule #7 in Table 9 and rule #14 in Table 11.

The shape of the adaptor allows better location and insertion of seatbelt into locking mechanism. This feature is modeled as parametric change to *position solid* function that aids the *reaching* activity. Rule #15 in Table 8 and rule #5 in Table 10 recommends a parametric change to *position hand* function that helps *reaching* activity. Similar to the OXO syringe, the seatbelt adaptor introduces couple of parametric changes for easy access.

For releasing the seat belt one has to *reach* and *manipulate*. The additional leverage for releasing the locking mechanism is a parametric change to function *guide solid*. Rule 5 in Table 9 puts forward that a parametric change to guide solid function can improve access to *manipulating* activity. However, rule #8 in Table 8 and rule #7 in Table 11 suggest a morphological change to the function of *guiding solid* for aiding *manipulating* activity. A morphological change for release of locking mechanism might be ergonomically located touch button.

Figure 36 shows a standard one-hole punch (left) and OXO one-hole punch (right). Figure 37 illustrates the difference between typical and universal one-hole punch through an action function diagram. OXO one-hole punch expands for leverage and folds for compact storage. The added leverage makes the activity of *grasping* easier. The product function of *guide solid* is morphologically changed. This change is in accordance with rule # 7 in Table 11, which suggests a morphological change to the function *guide solid* to aid the activity of *grasping*. OXO's one-hole punch belongs to same category as the Fiskars' soft touch scissors.

Figure 36. OXO's one-hole punch [88] (right) that expands for leverage and folds closed for compact storage. A typical one-hole punch is shown on the left [89]

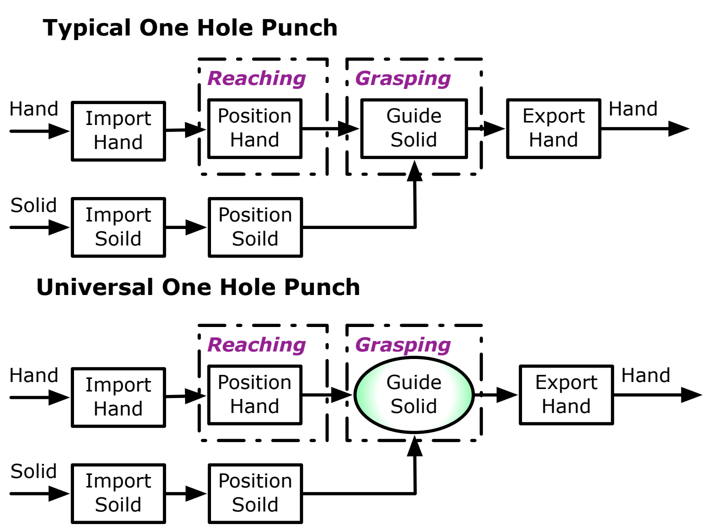


Figure 37. Actionfunction diagram of a typical one-hole punch (top) and universal one-hole punch (bottom)

Figure 38 shows a typical iron (left) and universal iron for the elderly (right). Figure 39 shows actionfunction diagram for both typical and universal design of iron. The temperature indicator in the universal design of iron is bolder. This change is in agreement with rule # 4 in the Table 9, which states that a parametric change to *indicate status* function improves the activity of *seeing*.

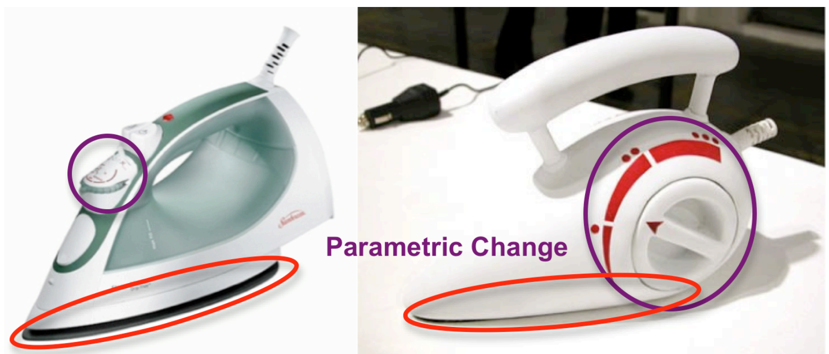


Figure 38. Iron for the elderly [90] (right) and a typical iron (left) [91]

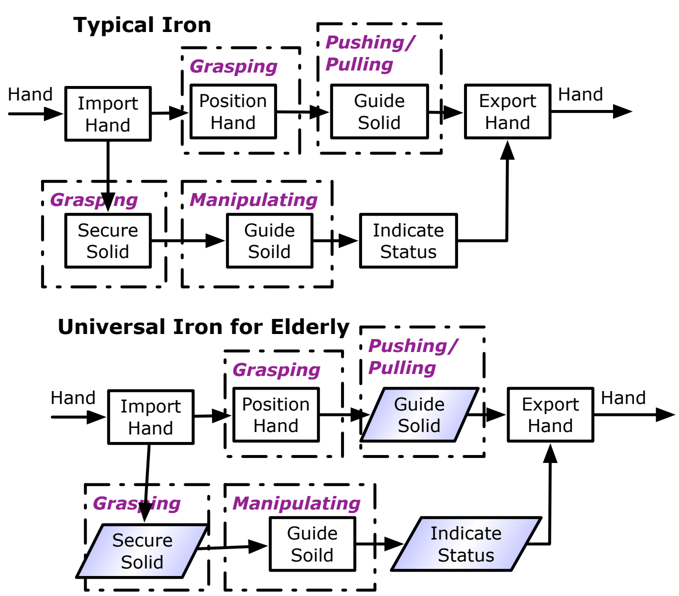


Figure 39. Actionfunction diagram of a typical iron (top) and universal iron for elderly (bottom)

The adjustment knob on the universal iron has additional leverage as opposed to round knob of typical iron. Rule # 15 in Table 11 recommends a parametric change to the function *secure hand* to aid the activity of *grasping*, which is very well represented by the example of iron.

The universal version of the iron is light in weight that makes it suitable for the older people. The lightweight feature makes the activity of *pushing/ pulling* easier and parametrically changes the *guide solid* function of the iron. The *push/pull* and *guide solid* pair can be improved either parametrically, morphologically or functionally as stated by rule #9 Table 8, rule # 10 in Table 11, and rule # 4 in Table 11 respectively. Note that this iron for elderly follows a parametric change to improve accessibility of *pushing/ pulling* activity.

The iron for the elderly has no exposed hot surfaces Again, rules generated in this research do not suggest protection from exposed hot surfaces. In our discussion we are not considering the 'safety' features.

Figure 40 shows a typical hammer on the left and a universal design of hammer on the right. Figure 41 illustrates the function change in the universal hammer through an actionfunction diagram for hammer.

The universal hammer provides a holder to secure a nail in place. The holder acts as a functional change, providing additional function of *positioning solid* and thus ease the *grasping* activity. Mostly, as suggested by rule #7 in Table 9 and rule #14 in Table 11, the accessibility for the pair *grasping* and *securing* is easily improved with a parametric change. However, the functional design change in universal hammer, for the pair *grasping* and *securing,* is on lines of rule #4 in Table 8.

Figure 40. Universal Hammer enables the user to hold a nail perpendicular with the help of a holder, eliminating the need to place fingers near the nail [92]. A typical hammer is shown on the left [93]

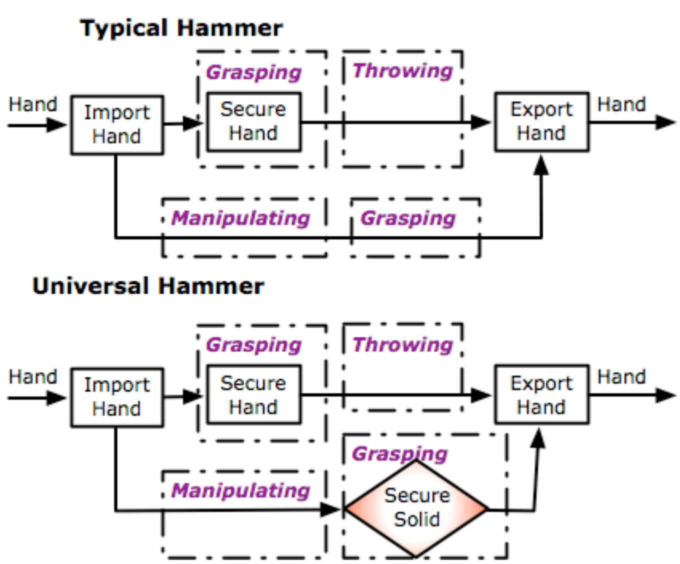


Figure 41. Actionfunction diagram of a typical hammer (top) and universal hammer (bottom)

Figure 42 shows a typical cutting board on top left. The single hand cook cutting board shown in Figure 42 provides additional functions like *secure solid* for the object to be cut or opened. Thus, one hand can perform cutting or peeling action while the other hand is free. The activity of *grasping* by other hand is eliminated as suggested by rule # 4 of Table 8, by adding a function of *secure solid*. The functional change is represented on actionfunction diagram of typical and universal cutting board shown in Figure 43.

Figure 42. The single hand cook cutting board [94] can be used with one hand. A typical cutting board is shown on top left [95]

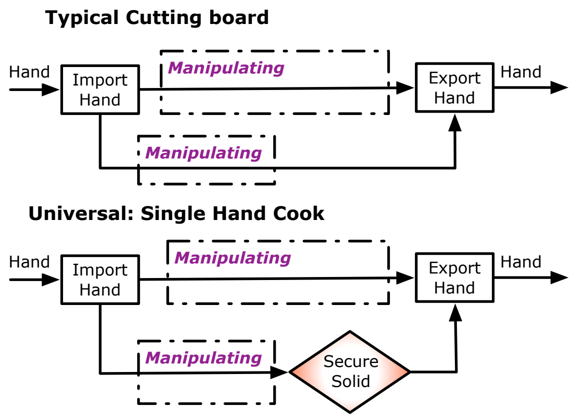


Figure 43. Actionfunction diagram of a typical cutting board (top) and universal cutting board (bottom)

Figure 44 shows a typical bicycle (left) and a universal design of bicycle (right). The universal design of bicycle includes a morphological change in the function *guide solid*, such that the user can pedal with hands instead of feet. Figure 45 illustrates the morphological difference between typical and universal bike with an actionfunction diagram.

Figure 44. Riding a bicycle using hand pedals (right) is morphologically different than a typical bicycle (left) [41]

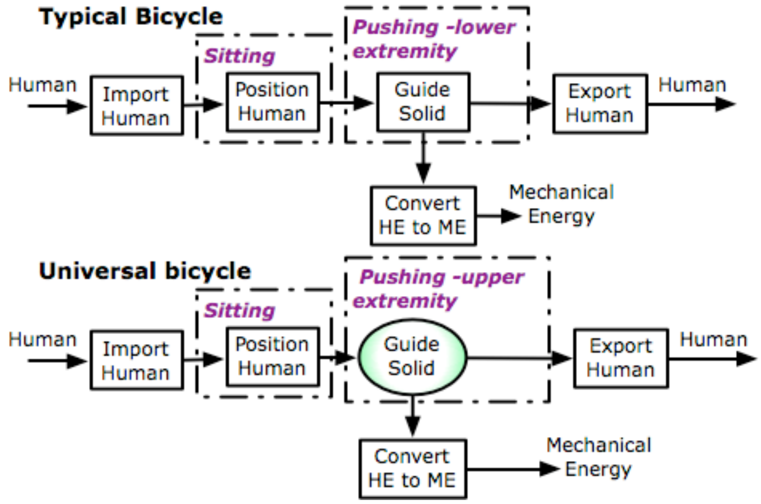


Figure 45. Actionfunction diagram of a typical bicycle (top) and universal bicycle (bottom)

In the universal design of bicycle, the activity is transformed from *pushing with lower extremity* to *pushing with upper extremity*. Rule # 10 in Table 11 suggests a morphological change for pair *pushing with lower extremity* and *guide solid*. Rule # 10 in Table 11 originated from the design of ford focus where the gas pedal can be operated not only by foot but also by hand.

Figure 46 shows a typical wine opener (left) and an automatic wine opener (right). Figure 47 shows actionfunction diagram for both typical and universal wine openers. The automatic wine opener eliminates the activity of *grasping* and *twisting* by adding the function of *guide solid.* This change is consistent with the consumer product, can opener studied in the analysis part. In the can opener, the electrical energy performs the functions of *guiding solid*. Rule # 6 in Table 11 suggests a functional change for this combination of user activity and product function.

Figure 46. Automating a wine opener adds functionality with electrical energy and eliminates the need for twisting the hand [41]

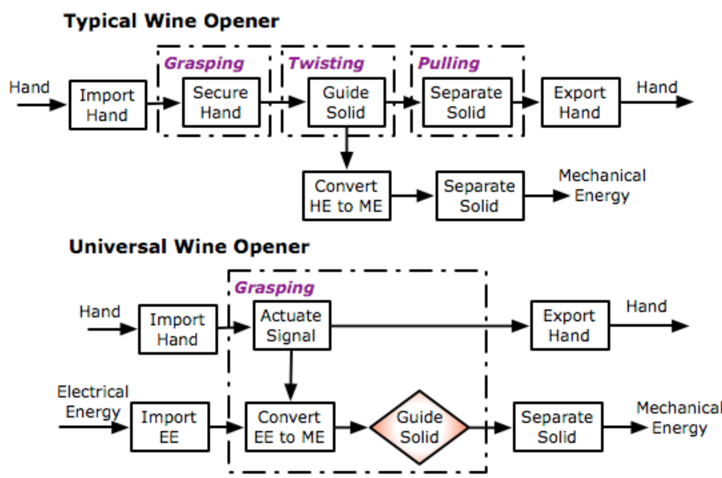


Figure 47. Actionfunction diagram of a typical wine opener (top) and universal wine opener (bottom)

Figure 48 shows typical eyewear (left) and Reykjavik Eyes eyewear (right). The Reykjavik Eyes eyewear is winner of the universal design award 09 [96]. It is made from one sheet of titanium and contains no screws and no hinges, eliminating the need of tiny spare parts. Figure 49 shows actionfunction diagram for typical and universal eyewear.

Figure 48. Reykjavik Eyes eyewear [96] is made from one sheet of titanium and contains no screws or hinges, eliminating the need of tiny spare parts. A typical eyewear is shown on the left [97]

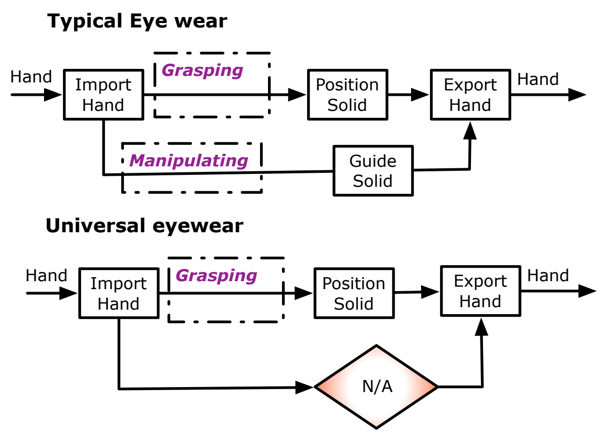


Figure 49. Actionfunction diagram of a typical eyewear (top) and universal eyewear from Reykjavik (bottom)

Hinges in the Reykjavik eyewear, providing the function of *guide solid*, are absent. Absence of hinges introduces a functional change to function *guide solid*. The functional change eliminates the activity of *manipulating* which is associated with fixing tiny screws. In the case of universal eyewear, the function *guide solid* and activity *manipulating* does not necessarily form a pair; hence the rules generated in this research cannot be directly applied here. As shown in Figure 49 the function *guide solid* is deleted. In my analysis, products in which functional parts are deleted are not studied exclusively. Reykjavik Eyes eyewear serves as example of product that cannot be designed based on the rules generated in this research.

5. CONCLUSION

In this thesis, I present new methods for analyzing existing universal products. These methods serve as elemental building blocks to capture elements of the design knowledge and tools contained in universal architectural design. The research uses the ICF to formally describe user activity, the Functional Basis to describe product function, and actionfunction diagrams as a framework to create a detailed understanding of the user activity and product function interaction.

In the context of designing new products, the actionfunction diagram is a useful framework. The diagrams guide the designer and provide a clear coupling between the interaction of user activity and customer need. Additionally the actionfunction diagrams indicate which functions are not directly related to a user activity thus indicating an element of the product design less likely to influence the universal nature of the design.

The classification of the changes as parametric, morphological, and functional provides a clear framework for comparing typical and universal designs. In practice, the strategies represented by the different changes exhibit design tradeoffs. In general, functional changes represent appreciable added design complexity and expense. On the other hand, morphological changes are moderately complicated. In some sense, the morphological changes appear more insightful or innovative. Parametric differences are generally the simplest and cheapest to implement.

The results of this research show promise in using the ICF to model user limitation. The ICF is well defined, organized, and gaining general acceptance in health services disciplines. However, the ICF does not provide enough detail in classifying a functional limitation to gain sufficient design insight that guides a designer. Detailed ergonomic data about limbs, joints, and motions involved may still be needed.

The design differences are listed against a set of user activities and product functions and are then input to data mining software to extract association rules. The rules obtained from the ADA guidelines, the architectural products and the consumer products are analyzed further. None of the rules overlap between the ADA guidelines and the consumer products. The architectural product category acts as transition between the ADA guidelines and the consumer products category.

The ADA guidelines can be extracted and translated to universal design of architectural products but not directly to consumer product design. Size and space relation between the user and the product is important for translating the rules. The rules that overlap between architectural products and consumer products have low support, which indicates that they are rare instances and not strong rules. Larger sets of consumer products, with a wide variety of applications, need to be studied to create a clearer understanding of universal consumer product design.

The main observations from the pilot study, conducted for the design of a universal washer, are summarized here. The actionfunction diagram provides a structured way to approach a problem in the early stage of design. It allows focusing on one user activity- product function pair at a time. The meaning of the user activities in the ICF lexicon is not obvious to product designers. Usage of the ICF lexicon for universal product design requires a detailed explanation of its scope and examples for each activity.

To validate the rules generated in this research, the applicability of the rules to 15 other products is studied. It is observed that the rules generated from design differences of the ADA guidelines and consumer products are mostly applicable. The rules generated do not necessarily suggest some of innovative design differences of universal consumer products. For instance, the universal design ideas of Reykjavik Eyes eyewear is not suggested by any of the rules generated. In a few cases the rules suggest a different form of design change for the same user-product interaction. As an example for the wine opener, the rule suggested a morphological change but the actual change is functional. If observed closely, it is seen that the rules generally translate between products having similar user-product relation.

6. FUTURE SCOPE

In this research, the activities and participation component (*d*) of the ICF is exclusively used. Future work will explore if other components of the ICF, particularly body functions and structures (*b*), would provide a superior, or perhaps complimentary, representation for user activity. Implementation of the qualifiers for ICF activities can also be studied in future.

The scope of current article is limited to physical impairments. Cognitive disabilities like Alzheimer's disease or autism are complicated and require careful consideration. Products that require fine motor skills or high cognitive ability needs to be studied further. In addition, the information technology and communication products are not assessed, as it is entirely a different domain.

Future work also includes increasing the sample size and scope of both architectural systems and consumer products studied. With a larger set of data, trends can be analyzed more formally to develop quantitative universal design guidelines.

The association rule based algorithm helps for quick analysis of the design features. Apriori algorithm outputs the trends followed by itemsets along with values of confidence, support, and lift for each rule. However, the Apriori algorithm is not programmed for this purpose and requires a thorough manual check of the association rules generated. Other better algorithm, perhaps one created in-house for analysis of the design knowledge should be considered in future.

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APPENDIX A

Table A1 provides the detailed analysis of section 4 of the ADA. User activity, ICF code, product function, and design change is provided for each of the ADA guidelines. Only the quantitative design guidelines are given for conciseness.

Table A1. Detailed analysis of section 4 of the ADA guidelines

#	Elements	Specifications	Change	User activity	ICF #	Product Function
4.2	Space Allowance and Reach	Wheelchair Passage Width	Parametric	Moving around	d455	Import / Export Human
		Width for Wheelchair Passing	Parametric	Moving around	d455	Import / Export Human
		Wheelchair Turning Space	Parametric	Moving around	d455	Import / Export Human
		Forward Reach	Parametric	Reaching	d4452	Position Hand
		Side Reach	Parametric	Reaching	d4452	Position Hand
4.2.4	Clear Floor or Ground Space for Wheelchirs	Size and Approach	Parametric	Moving around	d455	Import / Export Human
		Relationship of Maneuvering Clearance to Wheelchair Spaces	Parametric	Moving around	d455	Import / Export Human
4.3	Accessible Route	Width	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Passing space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Head Room	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Change in Levels	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
4.3.11	Areas of rescue assistance	Location and Construction	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Size	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Stairway Width	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Two-way Communication	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
4.4	Protruding Objects	Head Room	Parametric	Moving around	d455	Import / Export Human
4.5	Ground and Floor Surfaces	Carpet	Parametric	Moving around	d455	Import / Export Human
		Gratings	Parametric	Moving around	d455	Import / Export Human
4.6	Parking and Passenger Loading Zones	Parking Spaces	Parametric	Moving around outside the home and other buildings	d4602	Import / Export Human
		Vertical Clearance	Parametric	Moving around outside the home and other buildings	d4602	Import / Export Human

Table A1. Continued

		Passenger Loading Zones	Parametric	Moving around outside the home and other buildings	d4602	Import / Export Human
4.7	**Curb Ramps**	Slope	Parametric	Moving around outside the home and other buildings	d4602	Import / Export Human
		Width	Parametric	Moving around outside the home and other buildings	d4602	Import / Export Human
		Diagonal Curb Ramps	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Islands	Parametric	Moving around outside the home and other buildings	d4602	Import / Export Human
4.8	**Ramps**	Slope and Rise	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Clear Width	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Landings	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Handrails	Parametric	Moving around within buildings other than home	d4601	Secure Human
		Cross Slope and Surfaces	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Edge Protection	Parametric	Moving around within buildings other than home	d4601	Secure Human
4.9	**Stairs**	Treads and Risers	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Nosings	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Handrails	Parametric	Moving around within buildings other than home	d4601	Secure Human
4.10	**Elevators**	Automatic Operation	Functional	n/a	n/a	Position solid
		Hall Call Buttons	Parametric	Reaching	d4452	Position Hand
			Parametric	Manipulating	d4402	Guide Solid
			Functional	Seeing functions	b210	Indicate Status
		Hall Lanterns	Parametric	Reaching	d4452	Position Hand
			Functional	Seeing functions	b210	Indicate Status
		Raised and Braille Characters on Hoistway Entrances	Parametric	Communicating with - receiving - written messages	d325	Indicate Status
		Door Protective and Reopening Device	Functional	n/a	n/a	Guide Solid
			Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Door and Signal Timing for Hall Calls	Parametric	n/a	n/a	Import / Export Human
		Door Delay for Car Calls	Parametric	n/a	n/a	Import / Export Human
		Floor Plan of Elevator Cars	Parametric	Maintaining a body position	d415	Position Human
		Illumination Levels	Parametric	Seeing functions	b210	Indicate Status
		Car Controls	Parametric	Reaching	d4452	Position Hand
			Parametric	Manipulating	d4402	Guide Solid
			Functional	Communicating with - receiving - written messages	d325	Indicate Status

Table A1. Continued

		Car Position Indicators	Functional	Communicating with - receiving - spoken messages	d310	Indicate Status
			Functional	Communicating with - receiving - written messages	d325	Indicate Status
4.13	**Doors**	Clear Width	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Maneuvering Clearances at Doors	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Two Doors in Series	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Thresholds at Doorways	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Door Hardware	Parametric	Reaching	d4452	Position Hand
			Morphological	Manipulating	d4402	Guide Solid
		Door Closers	Parametric	n/a	n/a	Guide Solid
		Door Opening Force	Parametric	Pulling/ Pushing	d4450/ d4451	Guide Solid
		Automatic Doors and Power-Assisted Doors	Functional	n/a	n/a	Guide Solid
4.15	**Drinking Fountains and Water Coolers**	Spout Height	Parametric	Maintaining a body position	d415	Position Human
		Spout Location	Parametric	Reaching	d4452	Position Hand
		Controls	Morphological	Manipulating	d4402	Guide Solid
		Clearances	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
4.16	**Water Closets**	Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Height	Parametric	Maintaining a body position	d415	Position Human
		Grab Bars	Functional	Grasping	d4401	Secure Hand
		Flush Controls	Parametric	Reaching	d4452	Position Hand
			Morphological	Manipulating	d4402	Guide Solid
4.17	**Toilet Stalls**	Size and Arrangement	Parametric	Maintaining a body position	d415	Position Human
		Toe Clearances	Parametric	Maintaining a body position	d415	Position Human
		Grab Bars	Functional	Grasping	d4401	Secure Hand
4.18	**Urinals**	Height	Parametric	Maintaining a body position	d415	Position Human
		Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Flush Controls	Parametric	Reaching	d4452	Position Hand
			Morphological	Manipulating	d4402	Guide Solid
4.19	**Lavatories and Mirrors**	Height and Clearances	Parametric	Maintaining a body position	d415	Position Human
		Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Faucets	Morphological	Manipulating	d4402	Guide Solid
		Mirrors	Parametric	Caring for body parts	d520	Position Human

Table A1. Continued

4.20	**Bathtubs**	Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Seat	Functional	Maintaining a sitting position	d4153	Position Human
		Grab Bars	Functional	Grasping	d4401	Secure Hand
		Controls	Morphological	Manipulating	d4402	Guide Solid
		Shower Unit	Parametric	Washing whole body	d5101	Guide Liquid
			Morphological	Washing whole body	d5101	Guide Liquid
4.21	**Shower Stalls**	Size and Clearances	Parametric	Maintaining a body position	d415	Position Human
		Seat	Functional	Maintaining a sitting position	d4153	Position Human
		Grab Bars	Functional	Grasping	d4401	Secure Hand
		Controls	Parametric	Reaching	d4452	Position Hand
			Morphological	Manipulating	d4402	Guide Solid
		Shower Unit	Parametric	Washing whole body	d5101	Guide Liquid
			Morphological	Washing whole body	d5101	Guide Liquid
		Curbs	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
4.22	**Toilet Rooms**	Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
4.23	**Bathrooms, Bathing Facilities, and Shower Rooms**	Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Medicine Cabinets	Parametric	Reaching	d4452	Position Hand
4.24	**Sinks**	Height	Parametric	Maintaining a body position	d415	Position Human
		Knee Clearance	Parametric	Maintaining a body position	d415	Position Human
		Depth	Parametric	Reaching	d4452	Position Hand
		Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Faucets	Morphological	Manipulating	d4402	Guide Solid
4.25	**Storage**	Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Height	Parametric	Reaching	d4452	Position Hand
		Hardware	Morphological	Manipulating	d4402	Guide Solid
4.26	**Handrails, Grab Bars, and Tub and Shower Seats**	Size and Spacing of Grab Bars and Handrails	Parametric	Grasping	d4401	Secure Hand
		Structural Strength	Parametric	Grasping	d4401	Secure Hand
		Eliminating Hazards	Parametric	Grasping	d4401	Secure Hand
4.27	**Controls and Operating Mechanisms**	Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Height	Parametric	Reaching	d4452	Position Hand
		Operation	Morphological	Manipulating	d4402	Guide Solid
4.28	**Alarms**	Audible Alarms	Parametric	Hearing functions	b230	Indicate Status
		Visual Alarms	Functional	Seeing functions	b210	Indicate Status

Table A1. Continued

		Auxiliary Alarms	Functional	Hearing/ Seeing functions	b210-b230	Indicate Status
4.29	**Detectable Warnings**	Detectable Warnings on Walking Surfaces	Parametric	Communicating - receiving	d310-d329	Indicate Status
		Detectable Warnings at Hazardous Vehicular Areas	Parametric	Communicating - receiving	d310-d329	Indicate Status
		Detectable Warnings at Reflecting Pools	Parametric	Communicating - receiving	d310-d329	Indicate Status
4.30	**Signage**	Character Proportion	Parametric	Seeing functions	b210	Indicate Status
		Character Height	Parametric	Seeing functions	b210	Indicate Status
		Raised and Brailed Characters and Pictorial Symbol Signs (Pictograms)	Parametric	Communicating with - receiving - written messages	d325	Indicate Status
		Mounting Location and Height	Parametric	Seeing functions	b210	Indicate Status
4.31	**Telephones**	Clear Floor or Ground Space	Parametric	Maintaining a body position	d415	Position Human
		Mounting Height	Parametric	Reaching	d4452	Position Hand
		Hearing Aid Compatible and Volume Control Telephones	Parametric	Hearing functions	b230	Indicate Status
		Controls	Morphological	Manipulating	d4402	Guide Solid
		Telephone Books	Parametric	Reaching	d4452	Position Hand
		Cord Length	Parametric	Reaching	d4452	Position Hand
		Text Telephones	Functional	Communicating with written messages	d325	Sense/ Indicate Status
4.32	**Fixed or Built-in Seating and Tables**	Seating	Parametric	Maintaining a sitting position	d4153	Position Human
		Knee Clearances	Parametric	Maintaining a sitting position	d4153	Position Human
		Height of Tables or Counters	Parametric	Maintaining a sitting position	d4153	Position Human
4.33	**Assembly Areas**	Size of Wheelchair Locations	Parametric	Maintaining a sitting position	d4153	Position Human
		Placement of Listening Systems	Parametric	Hearing functions	b230	Indicate Status
		Types of Listening Systems	Morphological	Hearing functions	b230	Indicate Status
4.34	**Automated Teller Machines**	Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Reach Ranges	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Controls	Morphological	Manipulating	d4402	Guide Solid
		Equipment for Persons with Vision Impairments	Functional	Seeing functions	b210	Indicate Status
4.35	**Dressing and Fitting Rooms**	Clear Floor Space	Parametric	Moving around within buildings other than home	d4601	Import / Export Human
		Bench	Parametric	Sitting	d4103	Position Human
		Mirror	Parametric	Caring for body parts	d520	Position Human

APPENDIX B

ARCHITECTURAL PRODUCTS

B.1 Bathtub

Universal
Accessible Bathtub
http://tubcutters.com/
http://www.americanwheelchairs.com/specliftbathaqua.shtml

Non-Universal
Conventional Bathtub
http://www.rebathofthesoutherntier.com/product/conversions.php
http://www.plumbersurplus.com/images/prod/1/05350.jpg

B.2 Range cook top

Universal
Cook top with front controls
http://archrecord.construction.com/resources/images/0607whirlpoo l1.jpg

Non-Universal
Cooking range with rear controls
http://salestores.com/stores/images/images_747/FEF366EB.jpg

B.3 Microwave oven

Universal
Microwave
http://www.osd.fau.edu/Images/Kitchen%20up.JPG

Non-Universal
Microwave
http://www.governmentauctions.org/uploaded_images/microwave-759484.jpg

B.4 Conventional oven

Universal
Oven
http://www.dtapts.com/images/oneBedroom/huge/Kit-Range.JPG

Non-Universal
Oven
http://www.ease-abilitysolutions.com/images/oven-kraftmaid.jpg

B.5 Dishwasher

Universal
Dishwasher
http://products.geappliances.com/MarketingObjectRetrieval/Dispatcher?RequestType=Image&Name=033897.jpg&Variant=SpecPage

Non-Universal
Dishwasher
http://www.ssri.ca/assets/dishwasher%20after.jpg

B.6 Refrigerator

Universal
Refrigerator
http://www.builderonline.com/Images/dishwasher-and-refrigerator_tcm10-73348.jpg

Non-Universal
Refrigerator
http://bangalore.click.in/classifieds/images/19_10_2009_2_34_4_refrigerator.JPG

B.7 Kitchen drawer

Universal
Drawer
http://www.rezimo.com/wp-content/uploads//1213/kitchen_drawers_250.jpg

Non-Universal
Drawer
http://www.bayprofile.com/1112LaTerraceCir/photos/IMG_3236.JPG

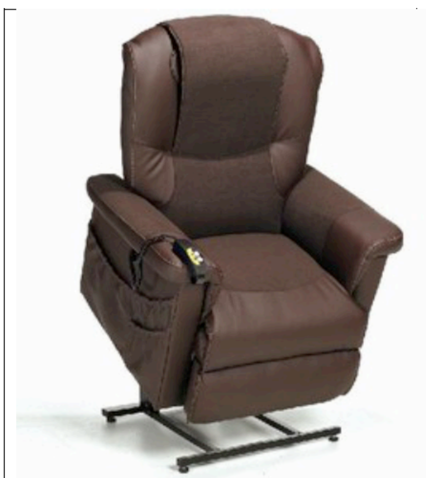
APPENDIX C
CONSUMER PRODUCTS

Note that the figures for Consumer products have been taken from the [98]

C.1 Toilet Seat -automatic

	
Lift UNIVERSAL	Standard NON-UNIVERSAL

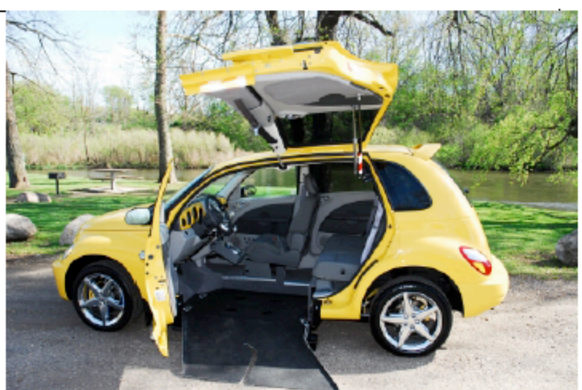
C.2 Recliner

	
Park Avenue Recliner UNIVERSAL	Regular Recliner NON-UNIVERSAL

C.3 Arm chair

	
Arm chair with lift UNIVERSAL	Arm chair NON-UNIVERSAL

C.4 PT Cruiser

	
Modified PT Crusier **UNIVERSAL**	Standard PT Crusier **NON-UNIVERSAL**

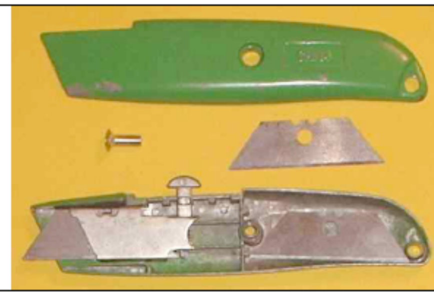
C.5 Adjustable Sink

 Manual Wash Basin Bracket with Sink  Electric Sink Bracket with Concealed Utilities.	
Adjustable Sinks **UNIVERSAL**	Drop-In Sink **NON-UNIVERSAL**

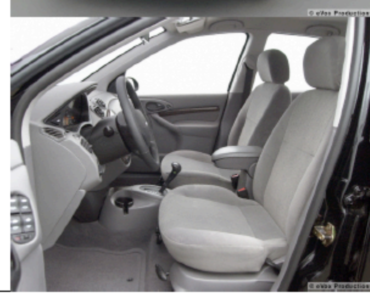
C.6 Scissors

	
Fiskars “Softouch Scissors” **UNIVERSAL**	Standard Scissors **NON-UNIVERSAL**

C.7 Box cutter

	
Fiskars "Rotary Cutter" **UNIVERSAL**	Utility Knife **NON-UNIVERSAL**

C.8 Ford Focus

   	  
2000 Ford Focus Modified **UNIVERSAL**	2000 Ford Focus Standard **NON-UNIVERSAL**

C.9 Can Opener

Gizmo T electric can opener **UNIVERSAL**	Mechanical can opener **NON-UNIVERSAL**

C.10 Pruners

American Standard Co. (Florian) "Ratchet Cut Pruners" **UNIVERSAL**	Pruning shears from Wikipedia **NON-UNIVERSAL**

C.11 Voice activated dialing

	
Voice Activated Phone **UNIVERSAL**	Normal Phone **NON-UNIVERSAL**

C.12 TV remote

	
Big Button Universal Control UNIVERSAL	Standard TV control NONUNIVERSAL

C.13 Tupperware

	
Tupperware "Wonderlier Bowls" **UNIVERSAL**	Sandwich Container **NON-UNIVERSAL** http://www.spacesavers.com/sandwich.html

VITA

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